Suppression of the longitudinal coupled bunch instability in DAFNE in collisions with a crossing angle

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ICFA mini-Workshop on "Mitigation of Coherent Beam Instabilities in particle accelerators" MCBI 2019, 23-27 Sep 2019, Zermatt, CH

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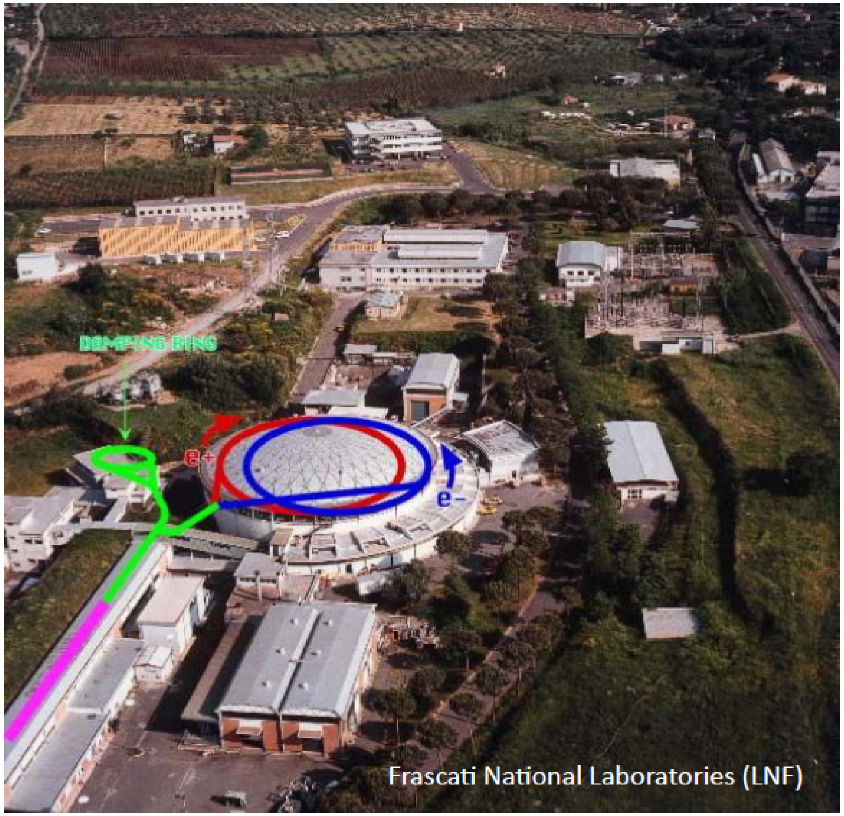
This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

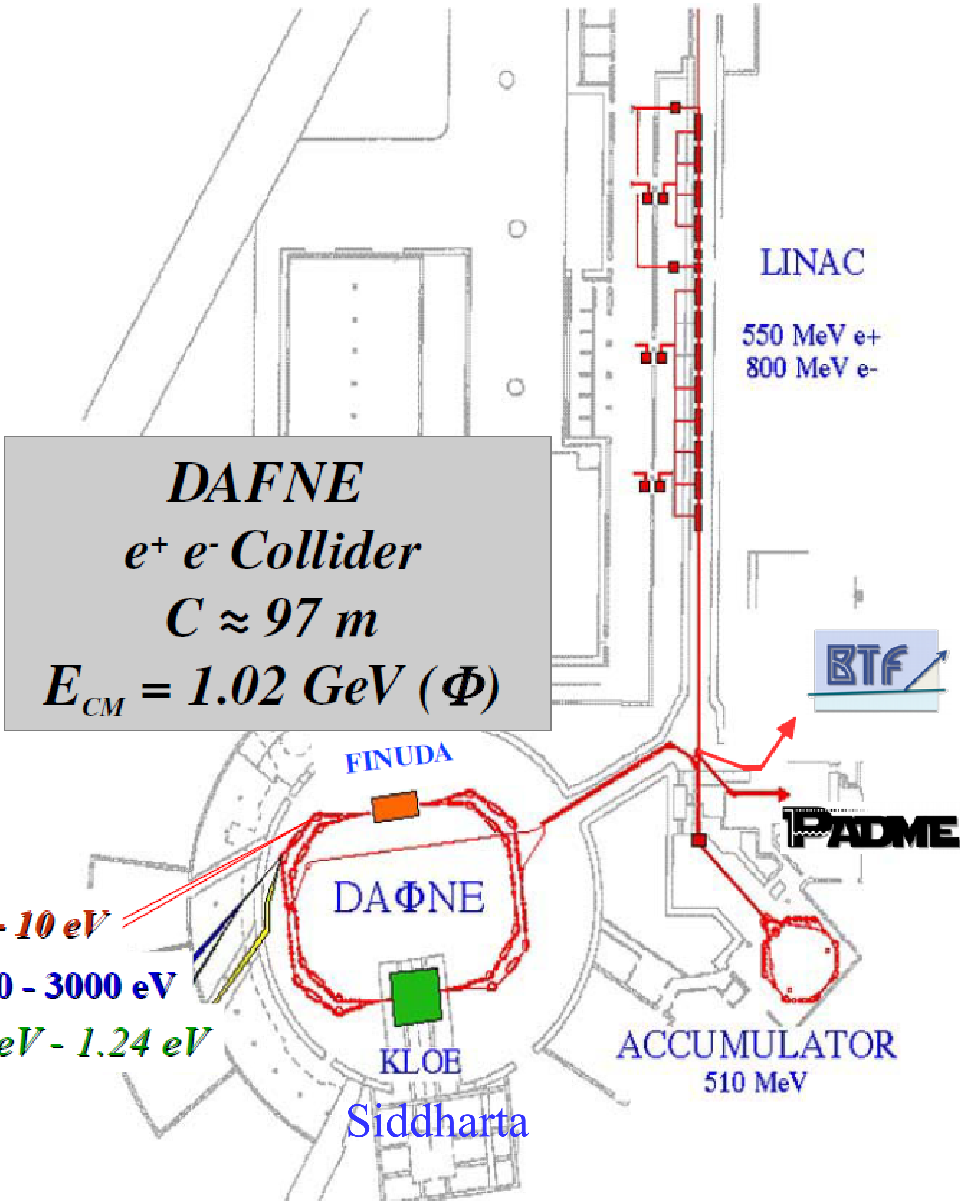
ARIES

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 (and in the following years for the KLOE-2 detector too).
- During the Siddharta 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 side bands.



Frascati National Laboratories (LNF)



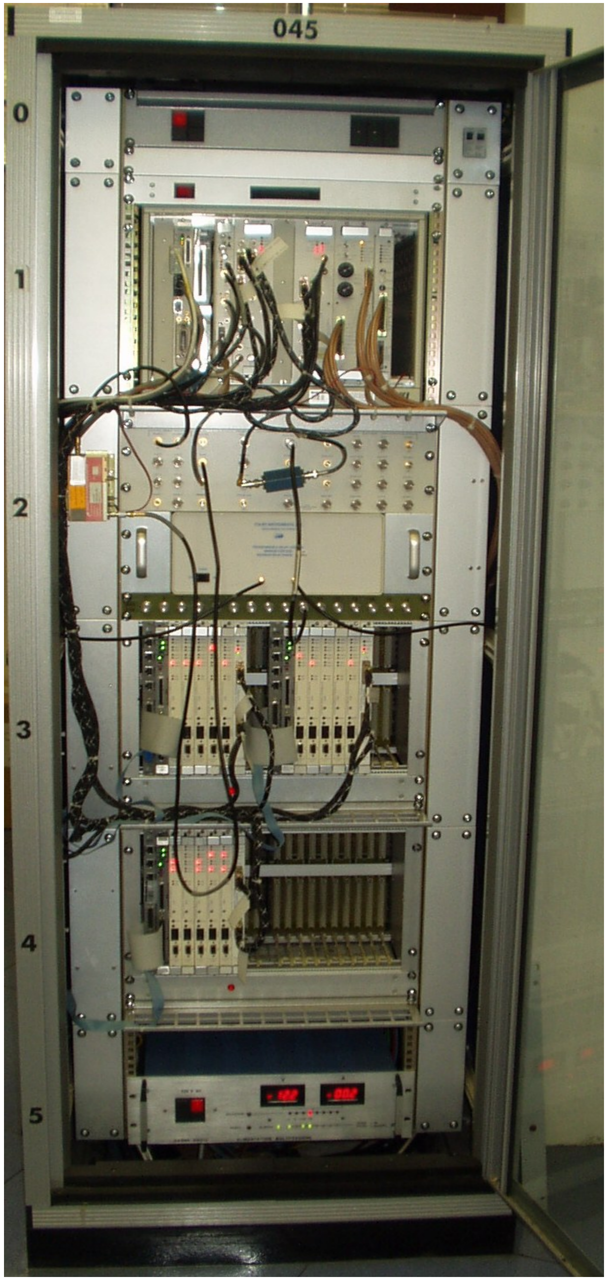
DAFNE
$e^+ e^-$ Collider
$C \approx 97$ m
$E_{CM} = 1.02$ GeV (Φ)

LNF are also part of the European synchrotron light Infrastructures network

Instrumentation

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

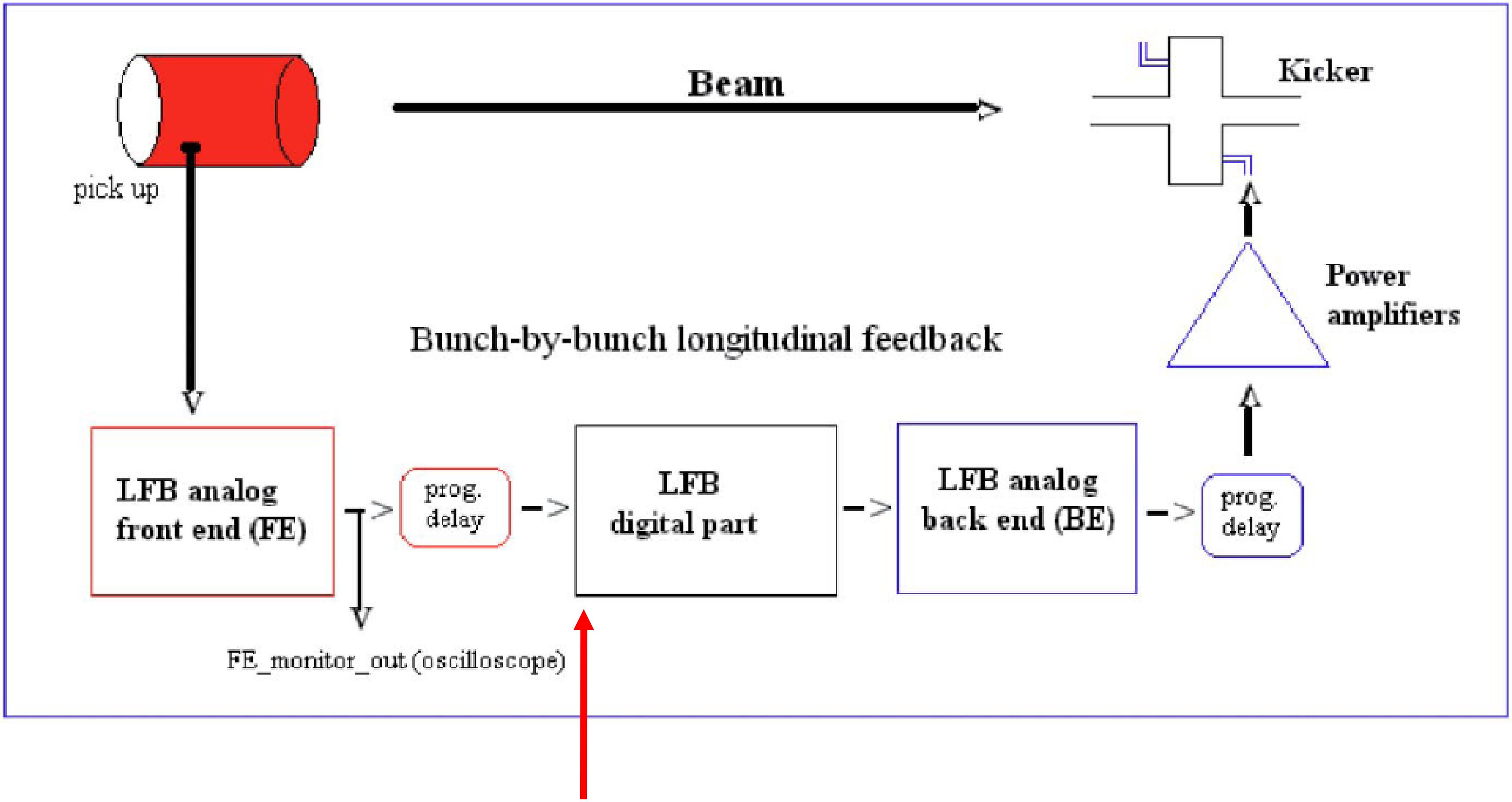
  - a commercial Real-time Spectrum Analyzer RSA 3303 by Tektronix
  - the diagnostics capabilities of the DAFNE longitudinal bunch-by-bunch feedback (developed in collaboration with SLAC and LBNL in 1993-96)



Acquisitions from the Spectrum Analyzer

- 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

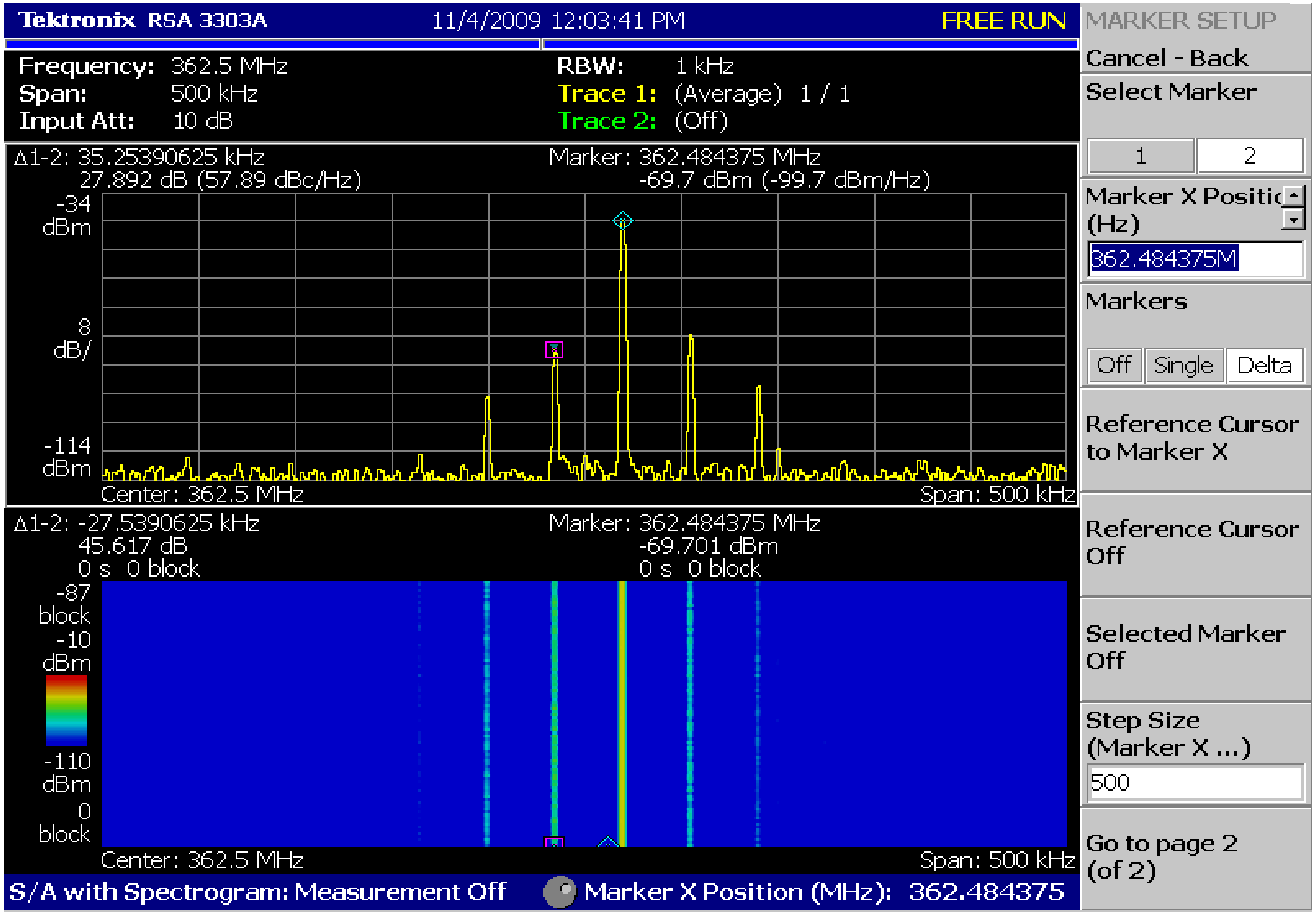
Block diagram of the longitudinal feedback system



Bunch-by-bunch record

Longitudinal sidebands in e+ beam

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



Tektronix RSA 3303A 11/4/2009 12:03:41 PM FREE RUN

Frequency: 362.5 MHz
Span: 500 kHz
Input Att: 10 dB
RBW: 1 kHz
Trace 1: (Average) 1 / 1
Trace 2: (Off)

Δ1-2: 35.25390625 kHz
27.892 dB (57.89 dBc/Hz)
Marker: 362.484375 MHz
-69.7 dBm (-99.7 dBm/Hz)

Δ1-2: -27.5390625 kHz
45.617 dB
0 s 0 block
Marker: 362.484375 MHz
-69.701 dBm
0 s 0 block

Marker X Position (Hz): 362.484375M
Step Size (Marker X ...): 500

S/A with Spectrogram: Measurement Off
Marker X Position (MHz): 362.484375

I+ = 200mA

e+ longitudinal feedback off

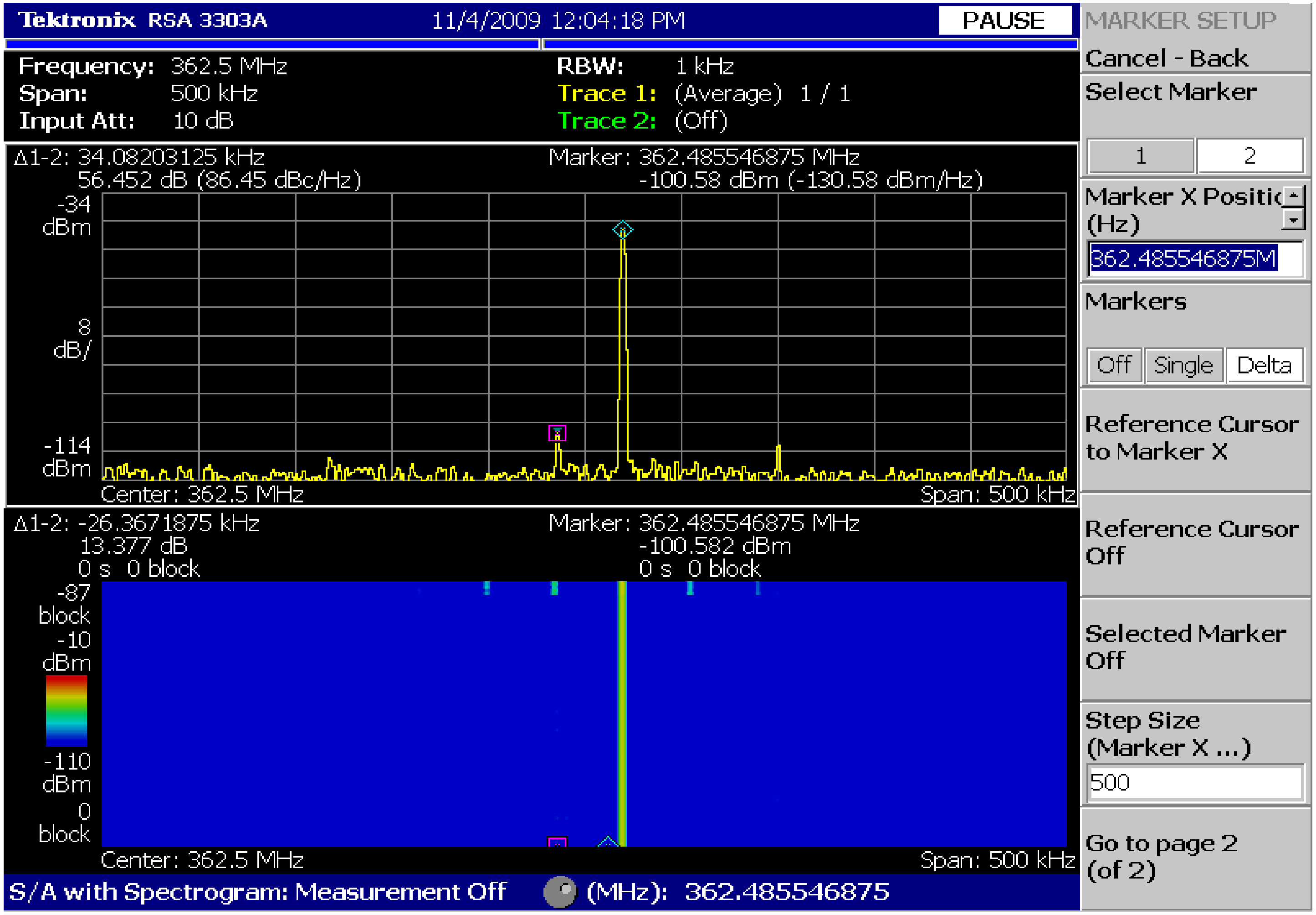
No collisions at the IP

The highest peak is the 118th harmonic

Other peaks: longitudinal sidebands

Longitudinal sidebands in e+ beam

colliding with 2A e- beam (100 bunches/120 buckets)



Tektronix RSA 3303A 11/4/2009 12:04:18 PM PAUSE

Frequency: 362.5 MHz
Span: 500 kHz
Input Att: 10 dB
RBW: 1 kHz
Trace 1: (Average) 1 / 1
Trace 2: (Off)

Δ1-2: 34.08203125 kHz
56.452 dB (86.45 dBc/Hz)
Marker: 362.485546875 MHz
-100.58 dBm (-130.58 dBm/Hz)

Δ1-2: -26.3671875 kHz
13.377 dB
0 s 0 block
Marker: 362.485546875 MHz
-100.582 dBm
0 s 0 block

S/A with Spectrogram: Measurement Off (MHz): 362.485546875

Marker X Position (Hz): 362.485546875M

Step Size (Marker X ...): 500

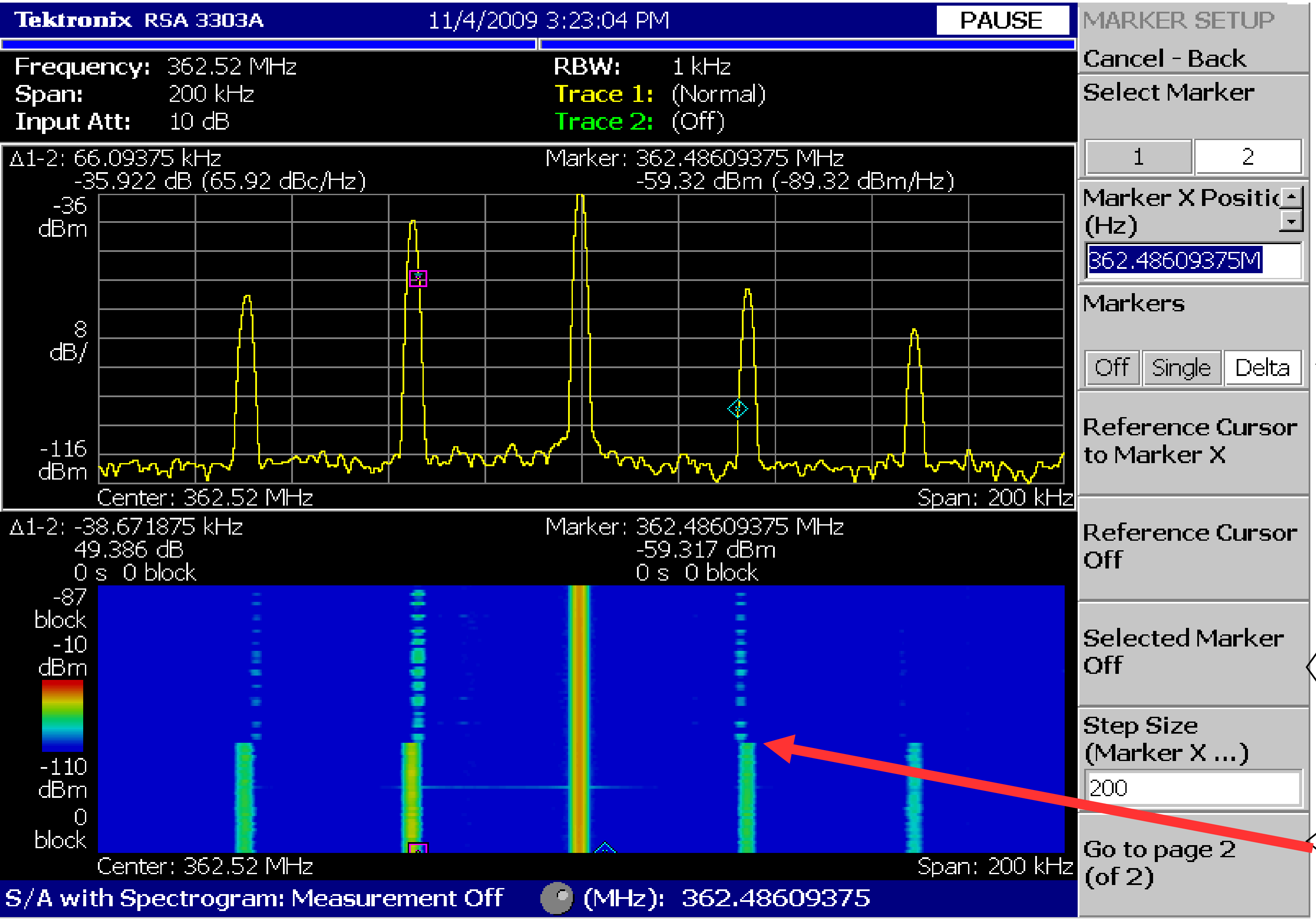
200 mA e+ beam

e+ longitudinal feedback off

In collision

Recorded by RSA 3303 spectrum analyzer

In collision ←→ out of collision



Tektronix RSA 3303A 11/4/2009 3:23:04 PM PAUSE

Frequency: 362.52 MHz
Span: 200 kHz
Input Att: 10 dB
RBW: 1 kHz
Trace 1: (Normal)
Trace 2: (Off)

Δ1-2: 66.09375 kHz
-35.922 dB (65.92 dBc/Hz)
Marker: 362.48609375 MHz
-59.32 dBm (-89.32 dBm/Hz)

Δ1-2: -38.671875 kHz
49.386 dB
0 s 0 block
Marker: 362.48609375 MHz
-59.317 dBm
0 s 0 block

S/A with Spectrogram: Measurement Off (MHz): 362.48609375

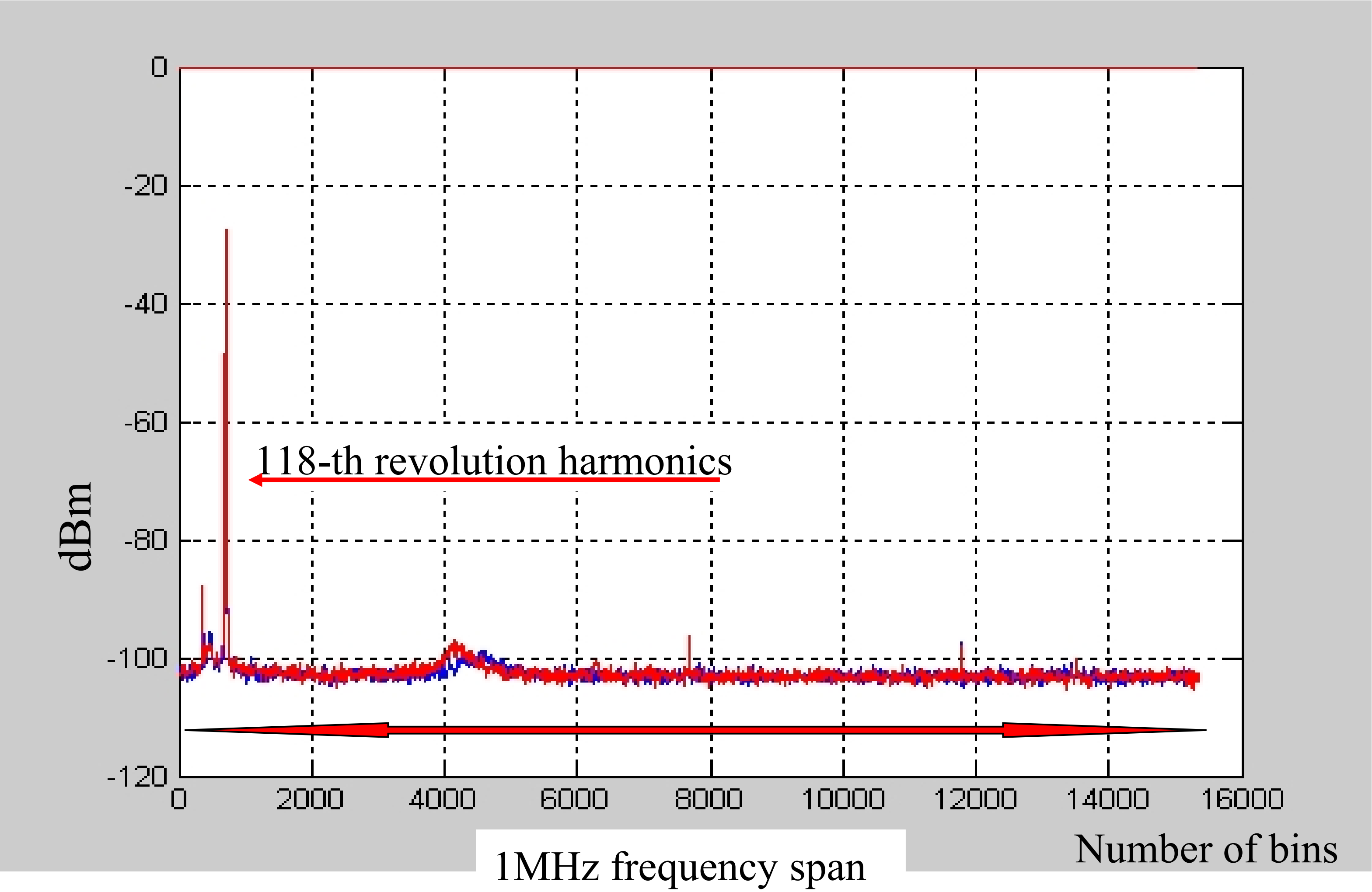
Marker X Position (Hz): 362.48609375M
Step Size (Marker X ...): 200

Last record

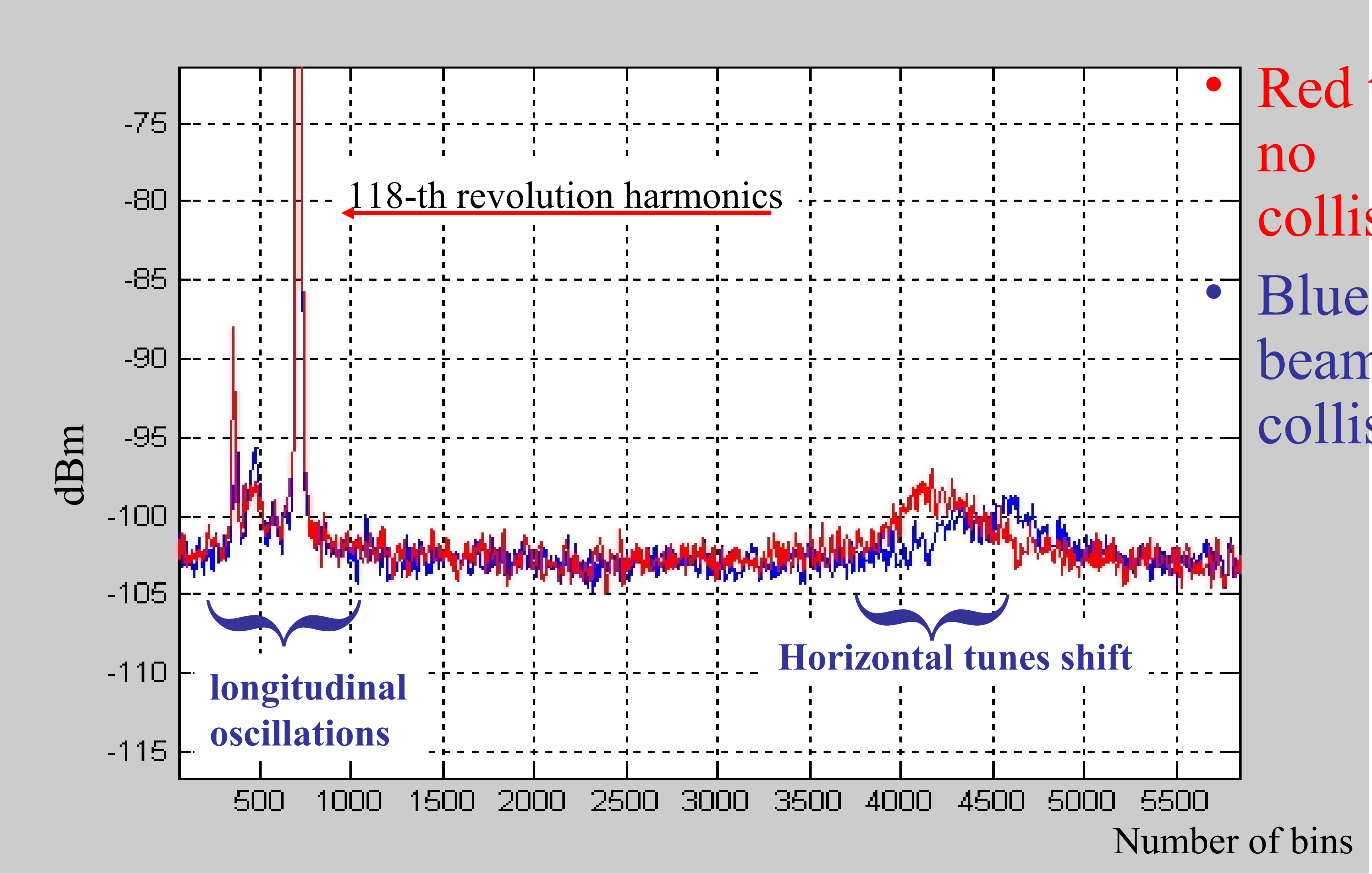
Last 60 sec. story

Tune shift

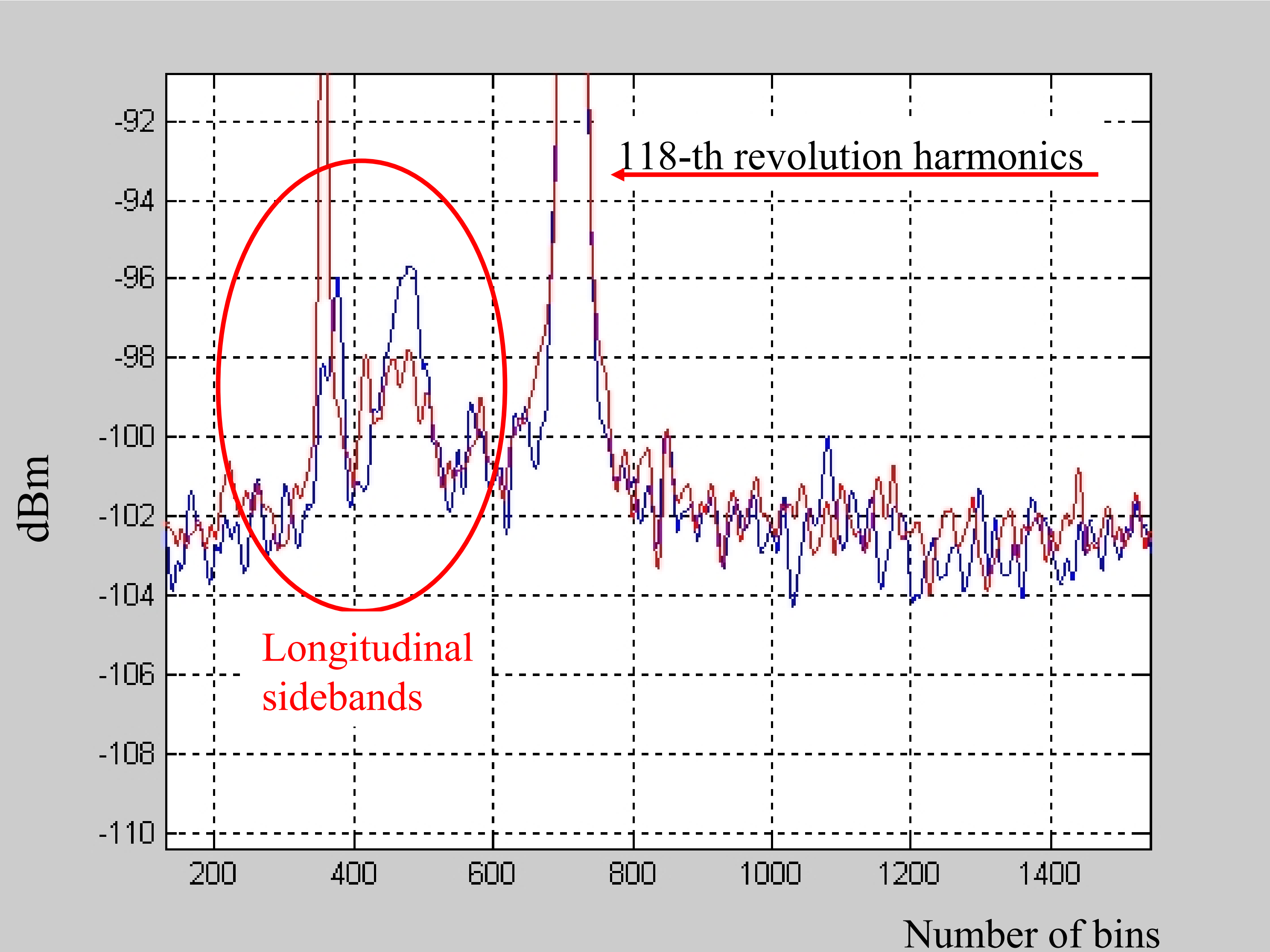
Data downloaded from the spectrum analyzer RSA3303 to a PC.
The highest peak is the e+ 118-th harmonics. Data are elaborated by MATLAB:
in **red** beams out of collision, in **blue** beams in collision.



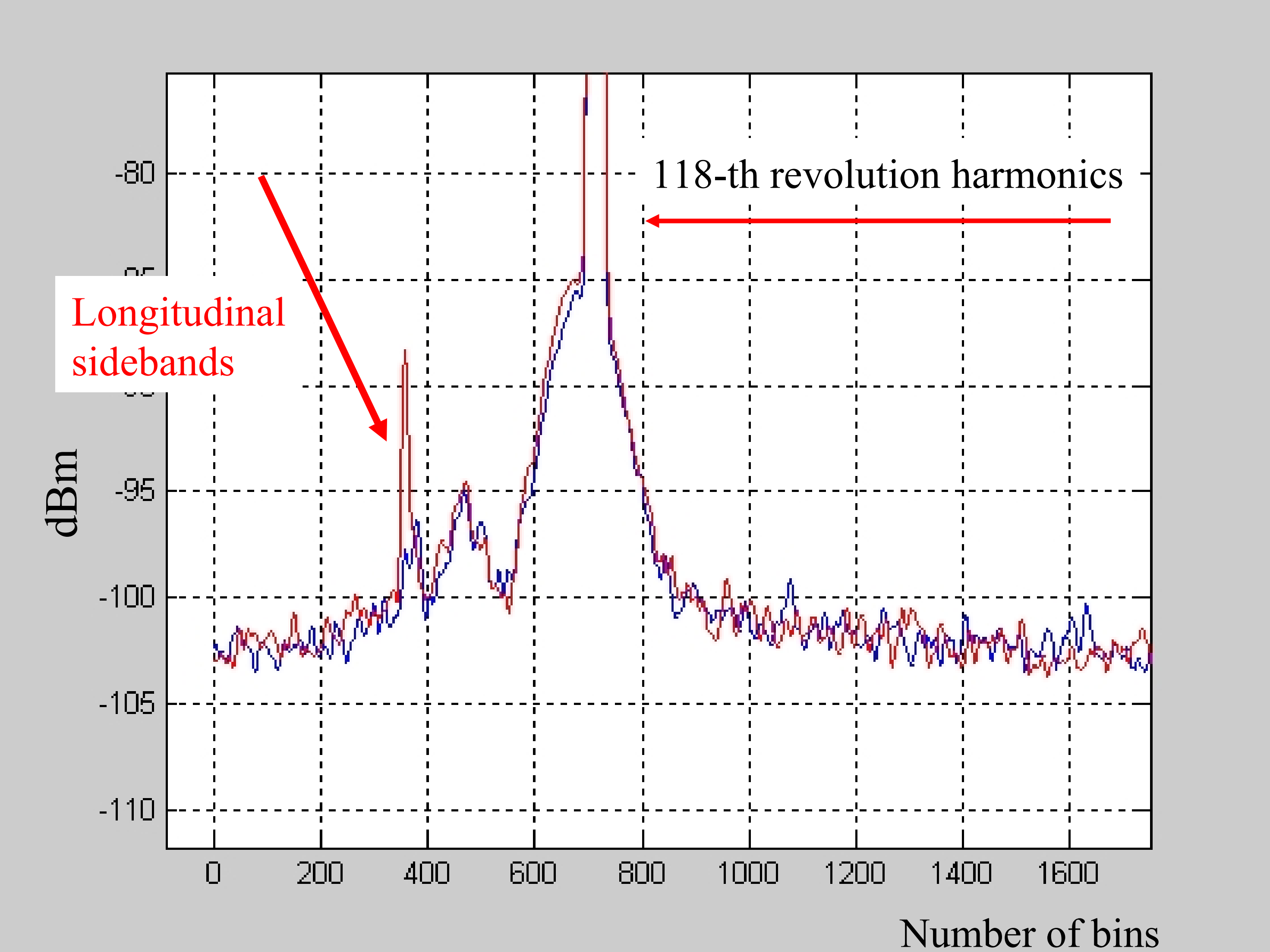
Zoom of the previous figure, showing the longitudinal and horizontal tunes



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



Zoom of the previous figure, particular of the longitudinal sidebands



118-th revolution harmonics

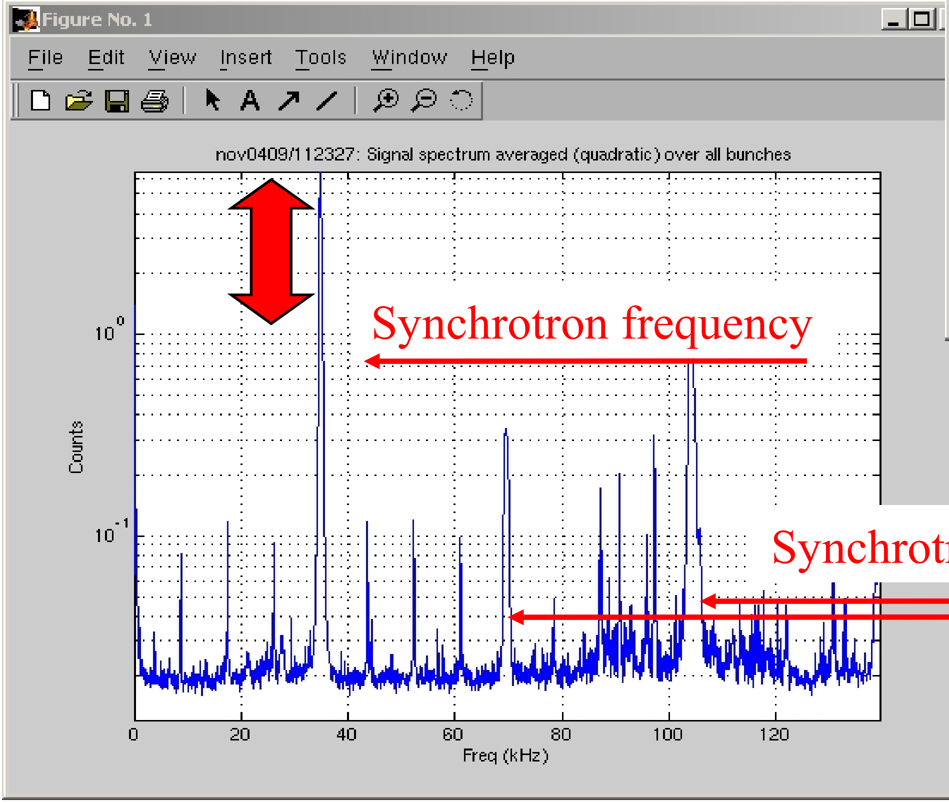
Longitudinal sidebands

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

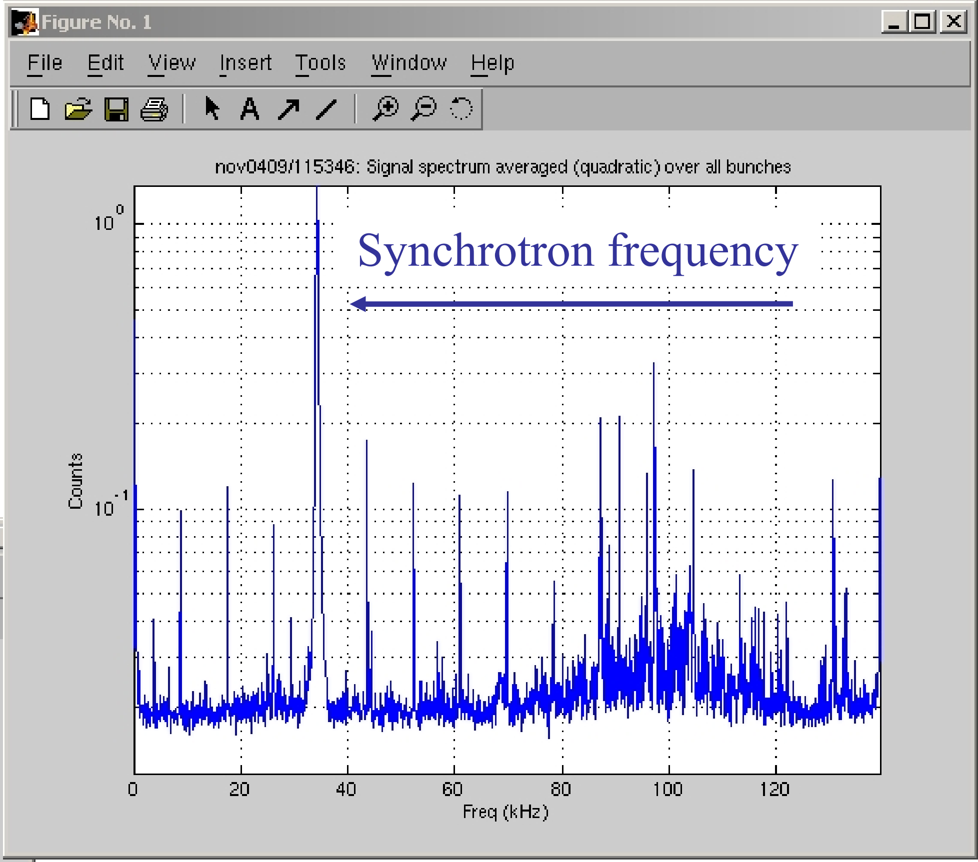
Diagnostics by the DAFNE longitudinal bunch-by-bunch feedback:

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

Out of collision



Synchrotron frequency

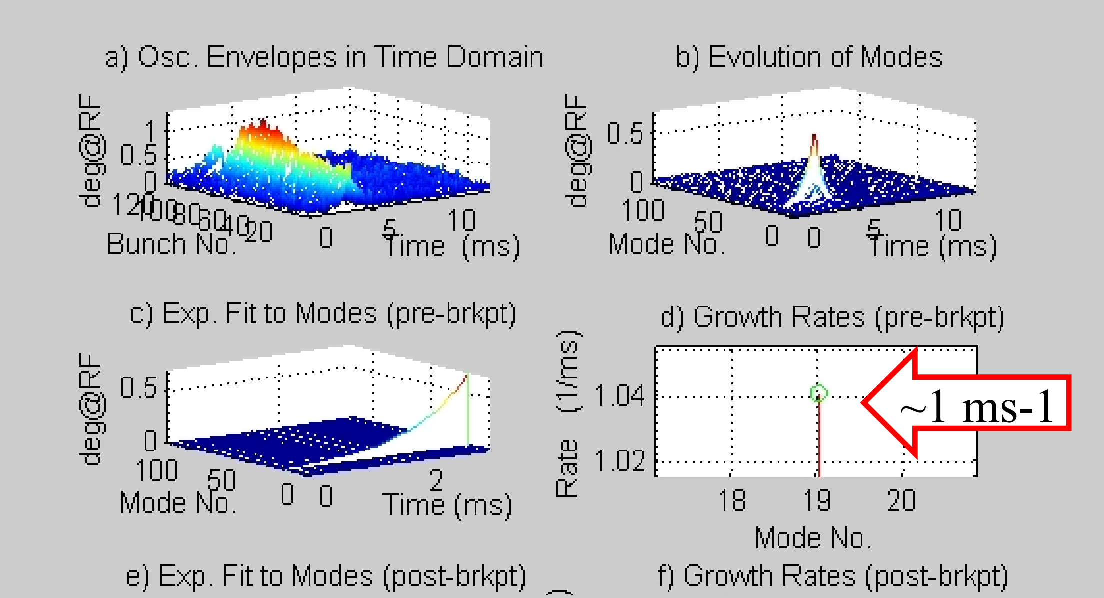


Synchrotron frequency

In collision

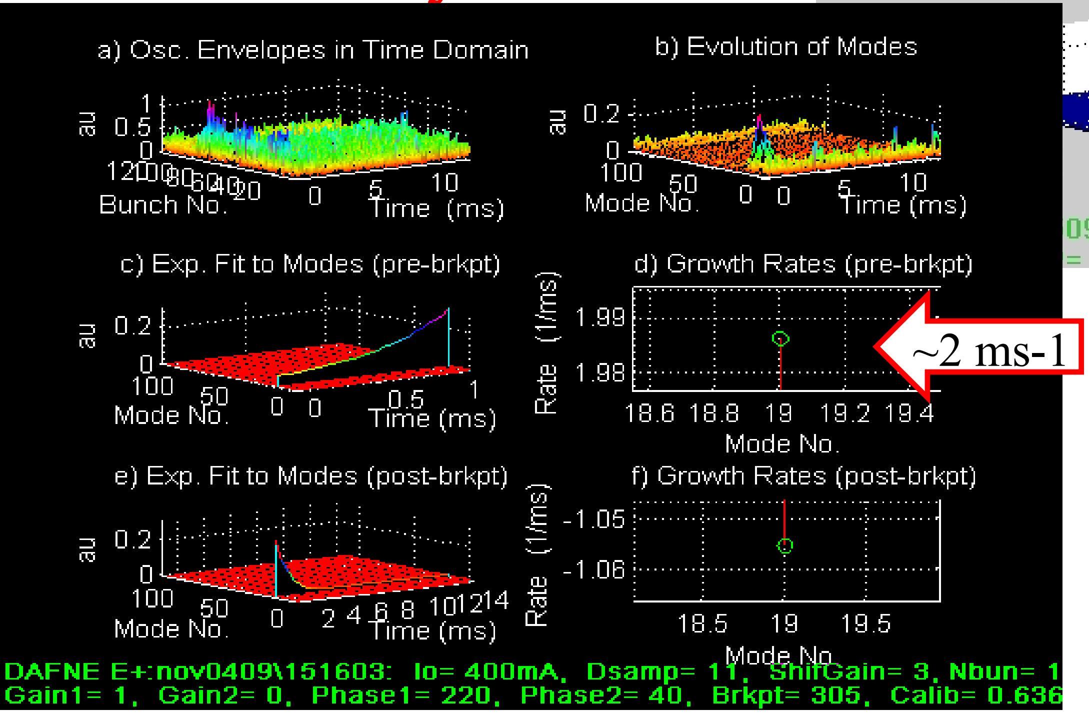
Synchrotron 2nd & 3rd harmonics

In collision e+ long. modal analysis



09\145636: Io= 350mA, Dsamp= 11, ShifGain= 3, Nbun= 12
= 0 Phase1= 220 Phase2= 40 Brkpt= 945 Calib= 0.6362

Out of collision longitudinal modal analysis



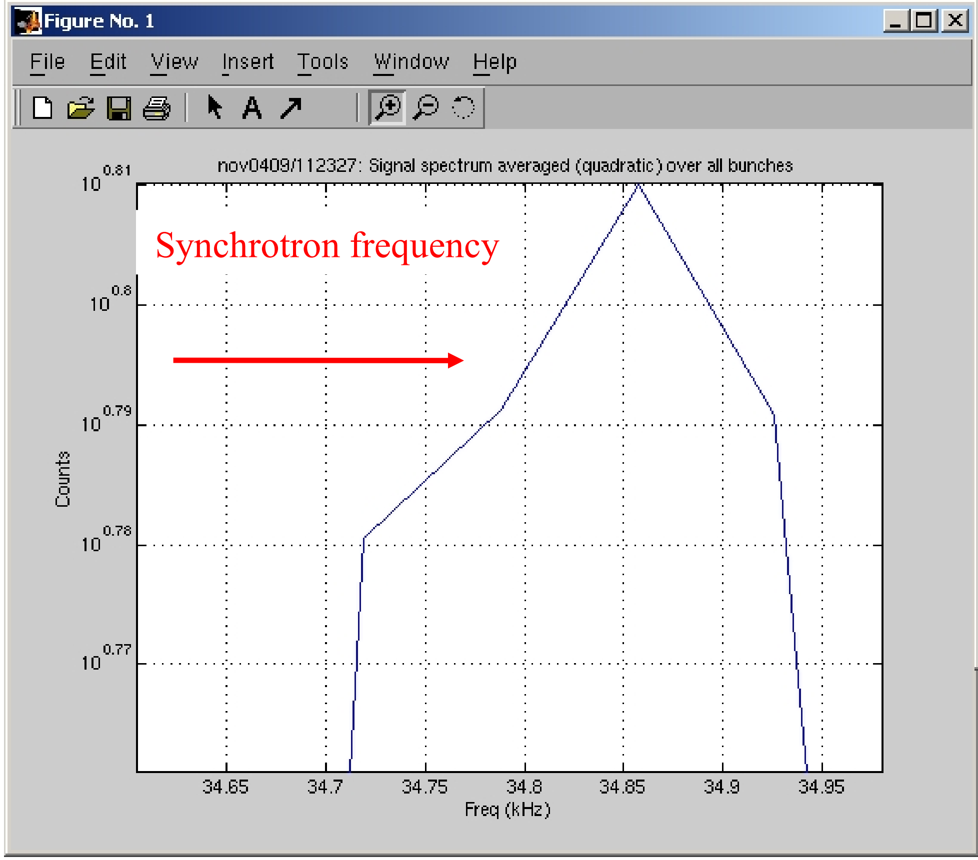
DAFNE E+:nov0409\151603: Io= 400mA, Dsamp= 11, ShifGain= 3, Nbun= 1
Gain1= 1, Gain2= 0, Phase1= 220, Phase2= 40, Brkpt= 305, Calib= 0.636

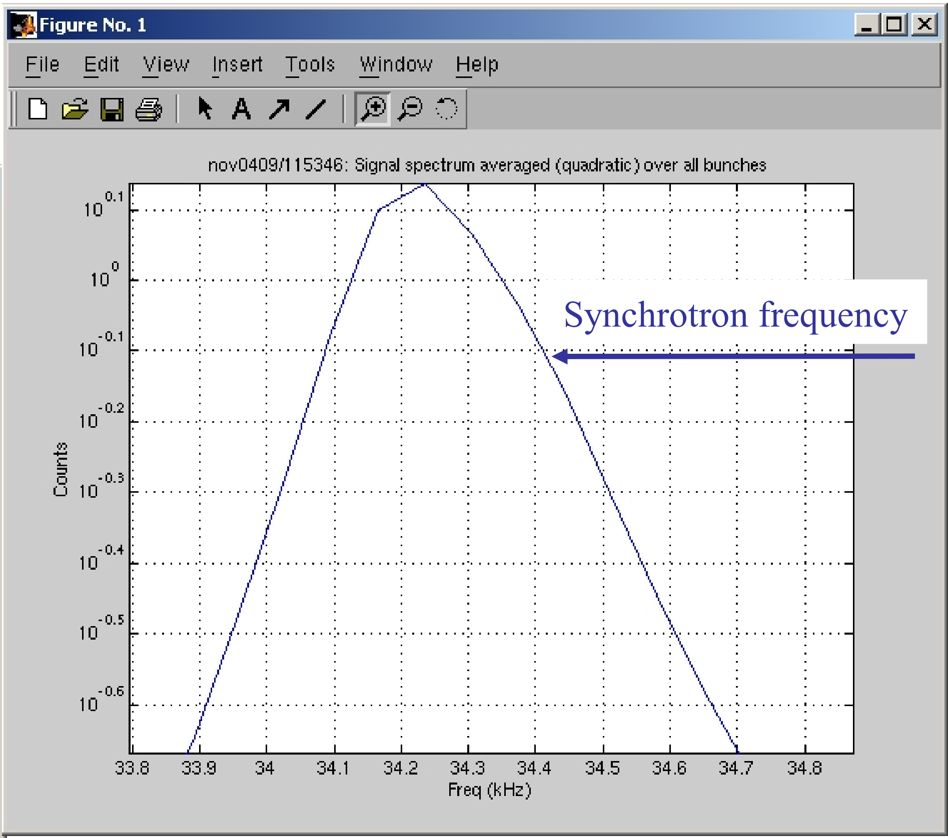
Analysis tools by S.Prabhakar, PHD thesis, SLAC-R-554, August 2001

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

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

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:

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

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 $\left(\sigma_y << \sqrt{\sigma_x^2 + \sigma_z^2 tg^2(\theta/2)}\right)$

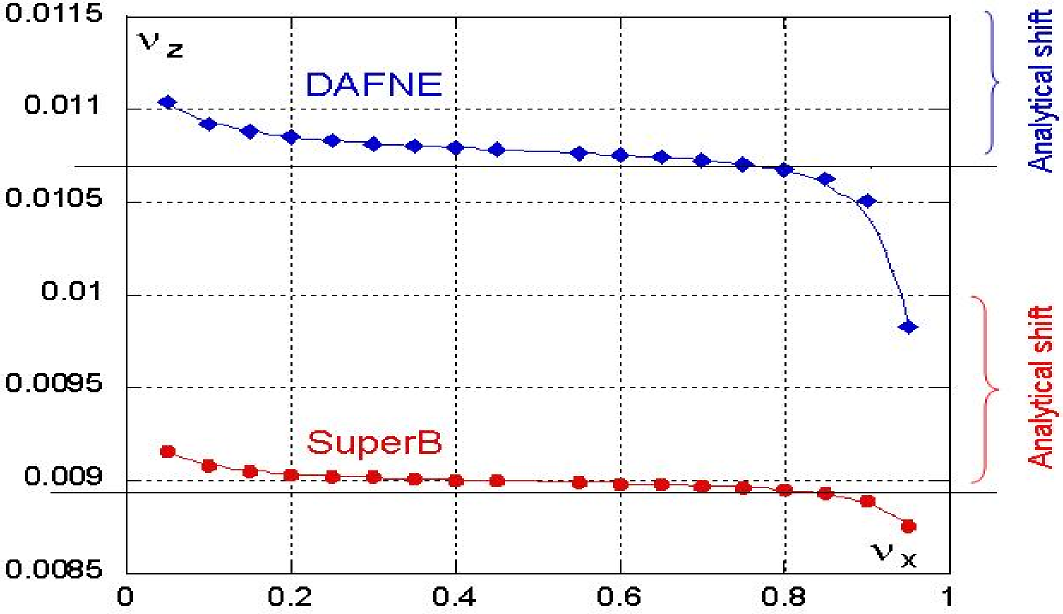
the tune shift expression can be further simplified to

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

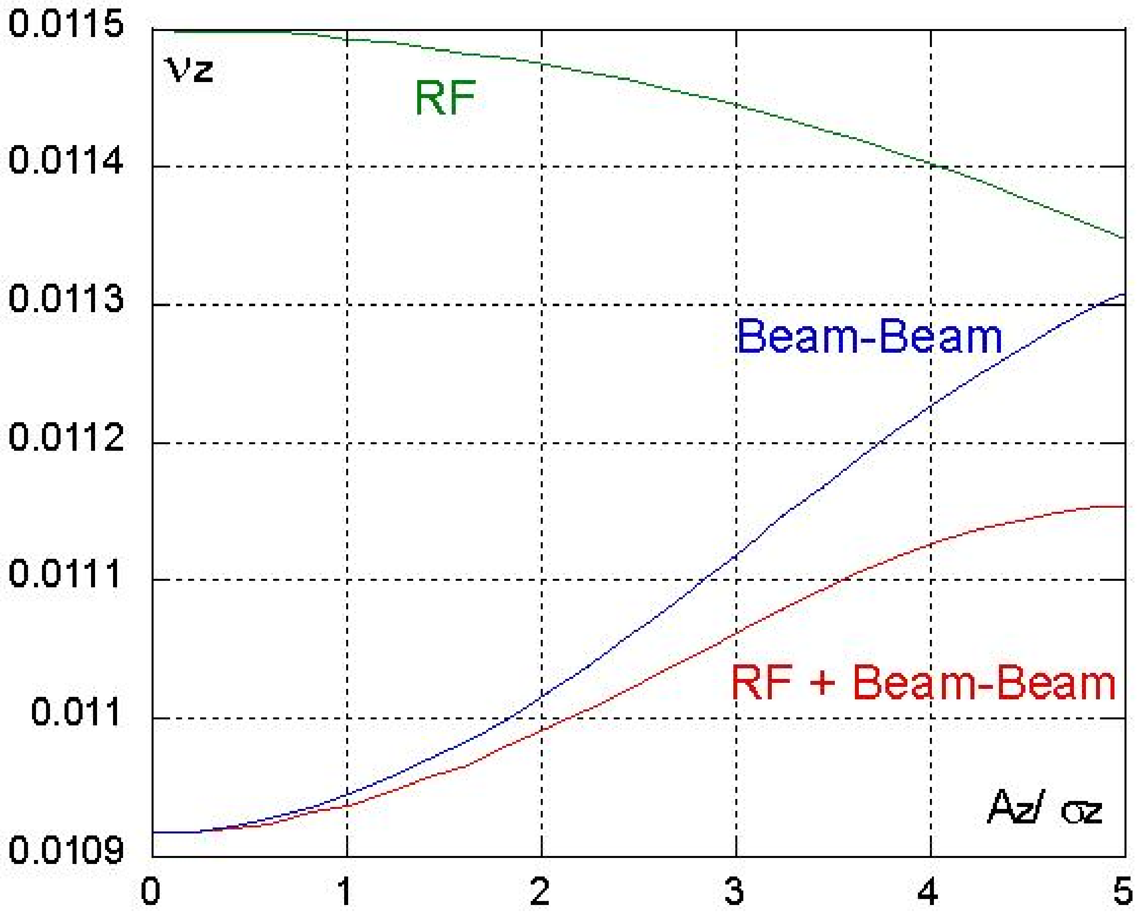
For the flat bunches the synchrotron tune shift practically does not depend on the vertical beam parameters. So, one should not expect any big variations due to crabbing and/or hour-glass effect. Since particles with very large synchrotron amplitudes practically do not "see" the opposite beam (except 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



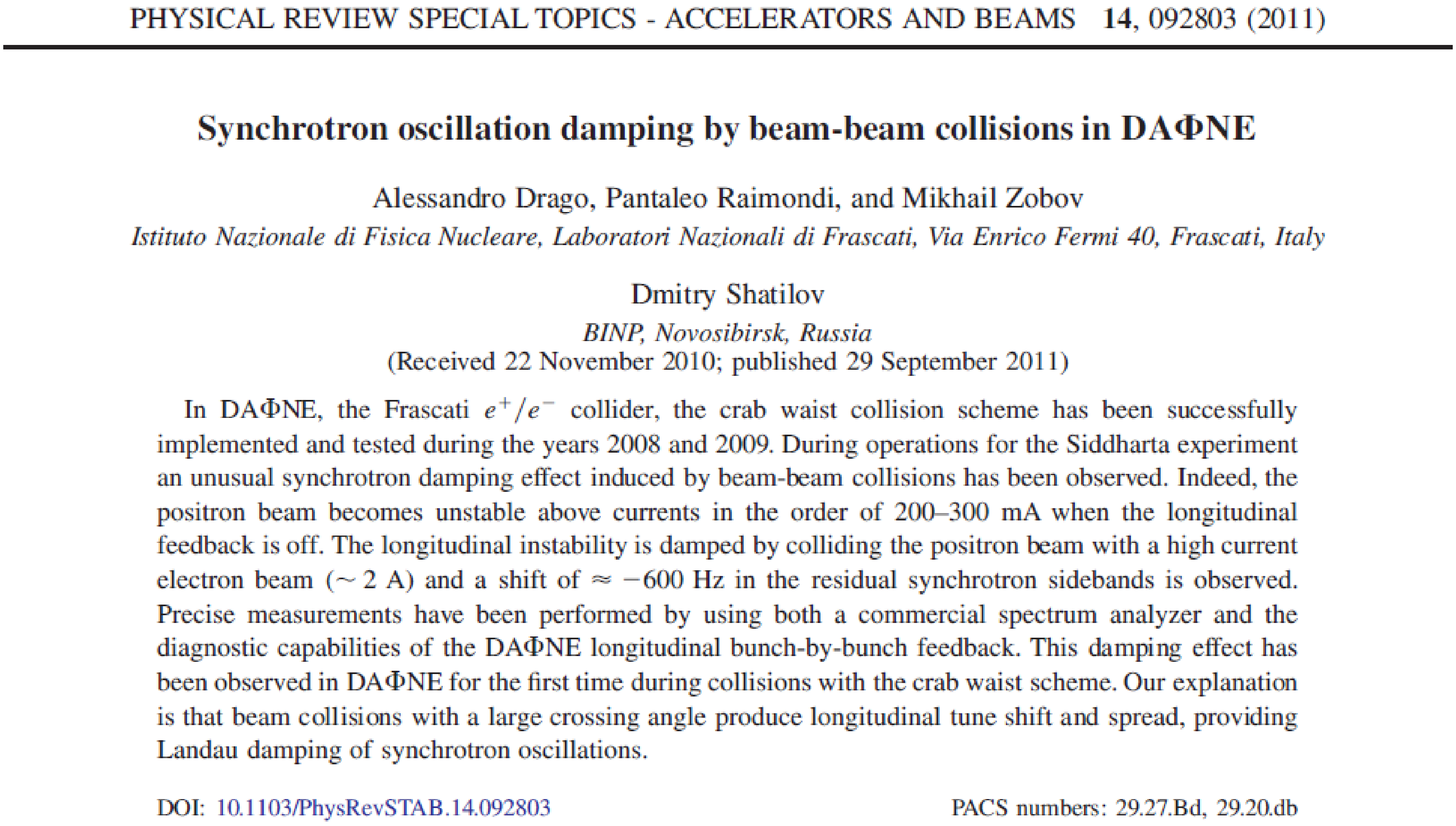
Synchrotron tune dependence on normalized amplitude of synchrotron oscillations (blue curve – tune dependence created by beam-beam collisions alone, green – RF nonlinearity alone, red – both contributions).

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.

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 bunch current $N = 0.9 \times 10^{10}$ and bunch length $\sigma_z = 1.6$ cm. These values give a result 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.**



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 092803 (2011)

Synchrotron oscillation damping by beam-beam collisions in DAΦNE

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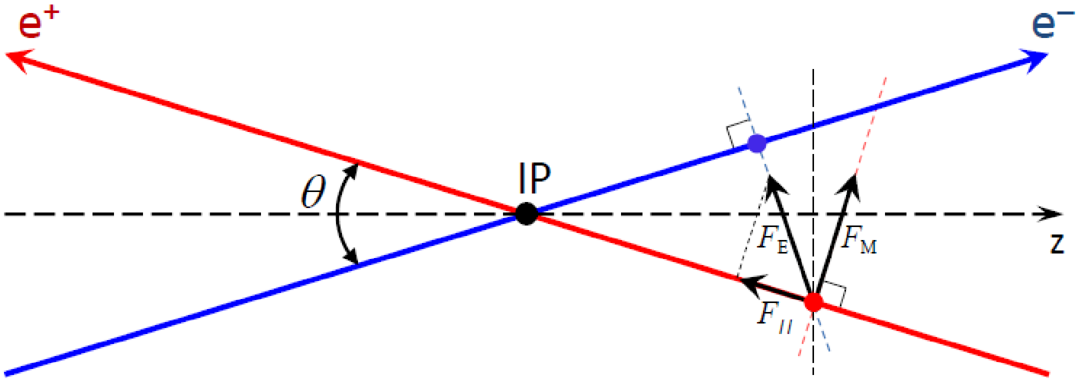
(Received 22 November 2010; published 29 September 2011)

In DAΦNE, the Frascati e^+/e^- collider, the crab waist collision scheme has been successfully implemented and tested during the years 2008 and 2009. During operations for the Siddharta experiment an unusual synchrotron damping effect induced by beam-beam collisions has been observed. Indeed, the positron beam becomes unstable above currents in the order of 200–300 mA when the longitudinal feedback is off. The longitudinal instability is damped by colliding the positron beam with a high current electron beam (~ 2 A) and a shift of ≈ -600 Hz in the residual synchrotron sidebands is observed. Precise measurements have been performed by using both a commercial spectrum analyzer and the diagnostic capabilities of the DAΦNE longitudinal bunch-by-bunch feedback. This damping effect has been observed in DAΦNE for the first time during collisions with the crab waist scheme. Our explanation is that beam collisions with a large crossing angle produce longitudinal tune shift and spread, providing Landau damping of synchrotron oscillations.

DOI: 10.1103/PhysRevSTAB.14.092803 PACS numbers: 29.27.Bd, 29.20.db

The Effect of Crossing Angle



- In the ultrarelativistic case, electro-magnetic field from the opposite bunch is compressed into a plane which is perpendicular to its trajectory.
- The kick from the opposite bunch consists of two components: electric and magnetic. Their absolute values are equal, but directions are different because of the crossing angle.
- Particles are accelerated in the region before IP and decelerated in the region after IP. The total energy change depends on the particle's longitudinal coordinate. This is equivalent to the appearance of a nonlinear RF cavity. The effect was experimentally observed at the DAΦNE collider [*Phys. Rev. ST Accel. Beams* 14 (2011) 092803]. !!!
- The crossing angle "at collision" is increased by beam-beam interaction.
- The total kick is orthogonal to the bisector of two trajectories, therefore $\delta p_z = 0$. It means that the center-of-mass energy at the IP is not affected, since $\sqrt{s} = 2\sqrt{|p_{z+}p_{z-}|}$ (see also the next presentation by P. Janot).

Conclusions

- An 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.
- 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.
- Simulations on this effect by LIFETRAC (Shatilov) and Guinea Pig (Perez) are carring on for FCC mainly to evaluate the delta of energy given by beam-beam kick at the IP (FCC week 2019).

Thank you for the attention !