Coherent Beam-Beam Effects at Hadron Colliders

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Outline

- **Coherent beam-beam modes:**
  - 1+1 bunch oscillations
  - multi-bunch modes
  - synchro-betatron oscillations
- **Instabilities of coherent beam-beam oscillations:**
  - beam-beam-driven instability (coherent resonances)
  - impedance-driven instabilities
- **Cures:**
  - restoration of Landau damping
  - head-tail damping
  - damping by synchro-betatron sidebands
- **Beam-beam compensation and coherent modes:**
  - tunespread compression with electron lenses

Coherent BB modes

- **Equal intensities, sizes and tunes: Σ- and π-modes (Yokoya et al., 1989)**

discrete Σ-mode (rigid-body): $\lambda = 0$

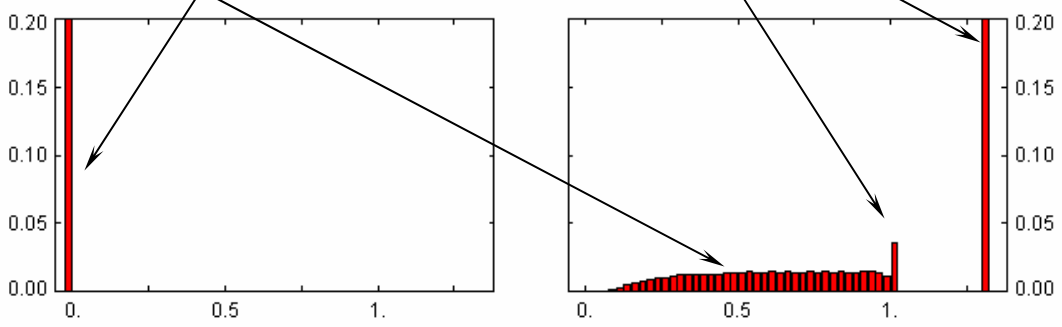
discrete π-modes:

round beams: $\lambda = 1.214$

flat beams (hor.): $\lambda = 1.330, 1.026, 1.002$

flat beams (ver.): $\lambda = 1.239$

+ continuum (0, 1) **in all cases**

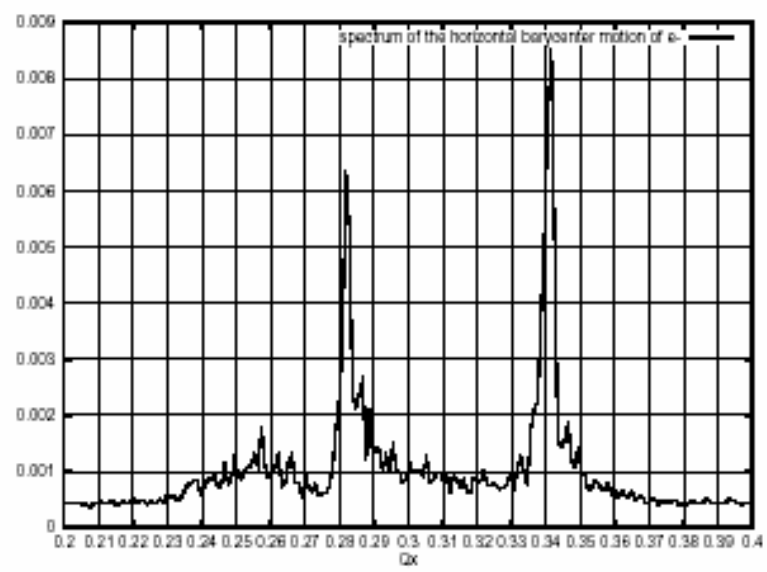


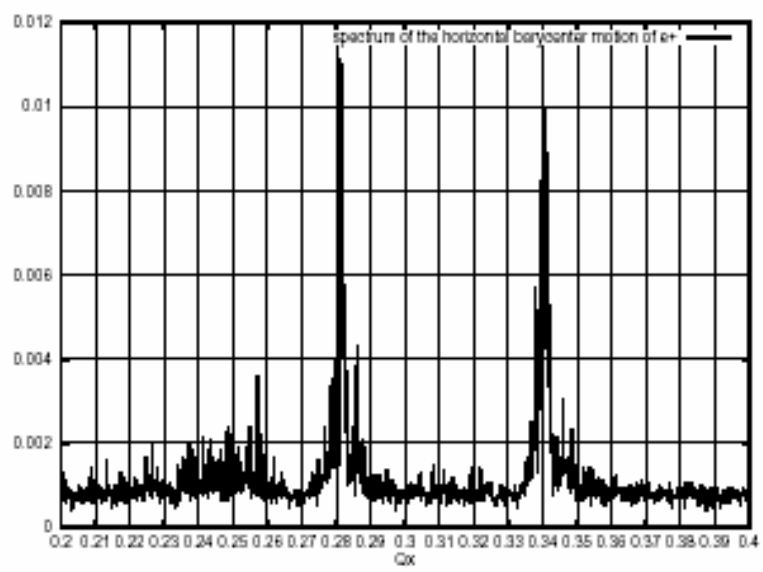
Spectral density of horizontal Σ (left) and π (right) oscillations in flat beams excited by a dipole kick

Observations of coherent BB modes

TRISTAN: ***precise measurements of λ (K.Yokoya et al., 1989)***

LEP:

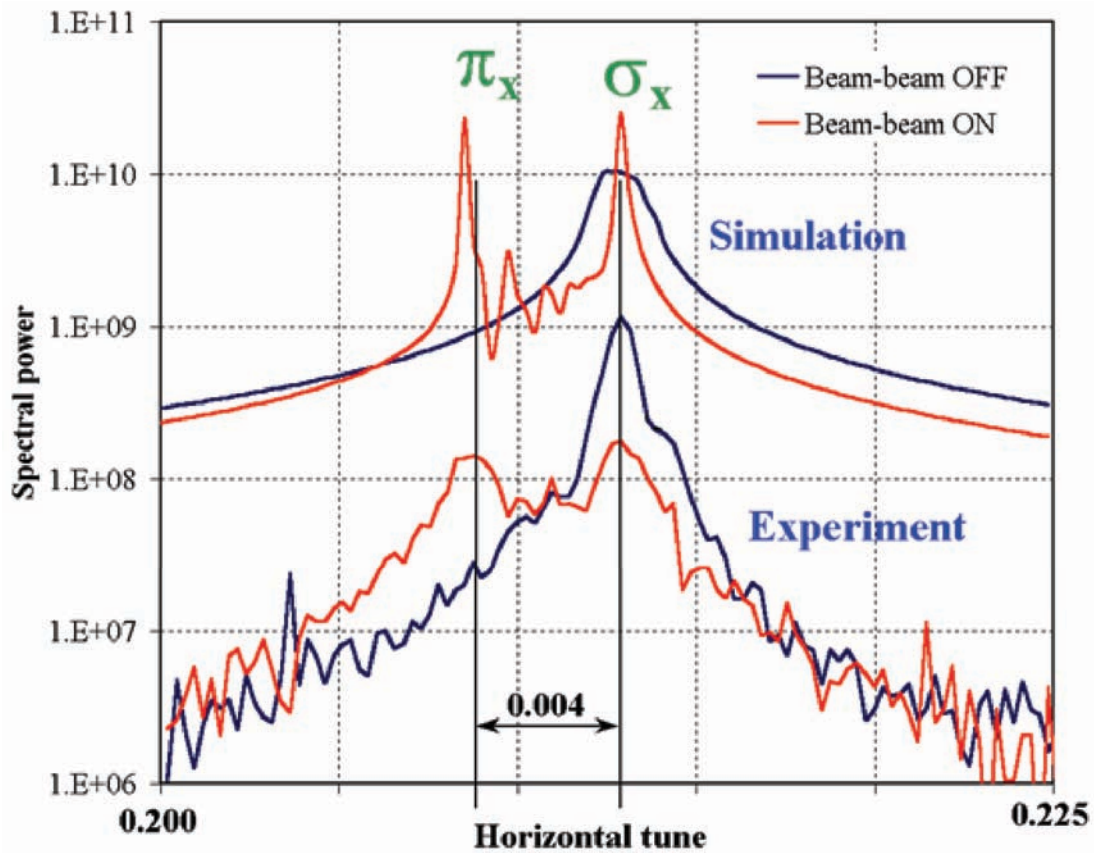




Spectra of horizontal oscillations in LEP of two bunches colliding at two IPs: left – electron beam, right – positron beam (courtesy of G.Morpurgo)

Observations of coherent BB modes

RHIC:



Measured Σ-π tunesplit:

0.004

Expectation:

$1.214\xi_x = 0.0036$

Spectra of two colliding p-bunches in RHIC (courtesy of W.Fischer)
Simulations by M.Vogt et al. (2002)

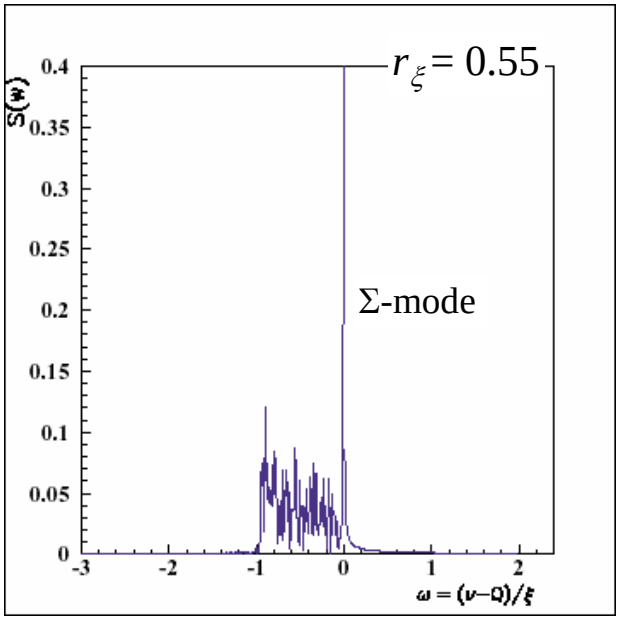
Nascence of coherent BB modes

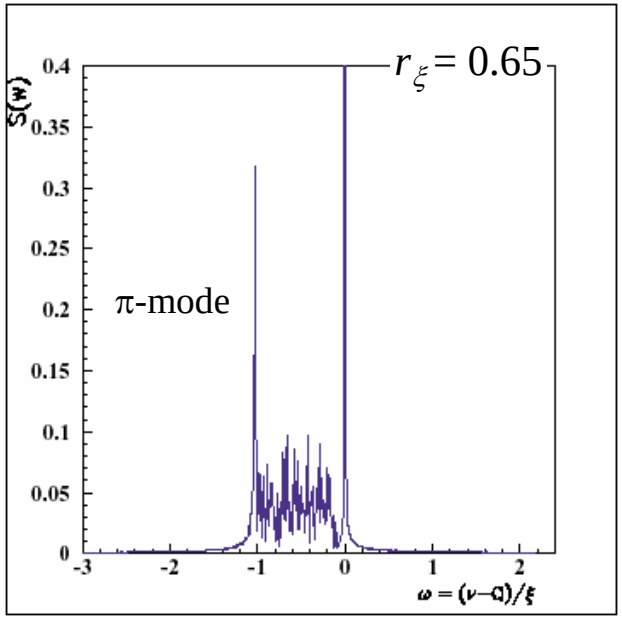
Possible problem:

Large gap between π-mode and continuum may switch off Landau damping in the strong-strong regime (J.Gareyte, 1989).

Why this has not been observed in SPS and Tevatron Run I? One of the reasons:

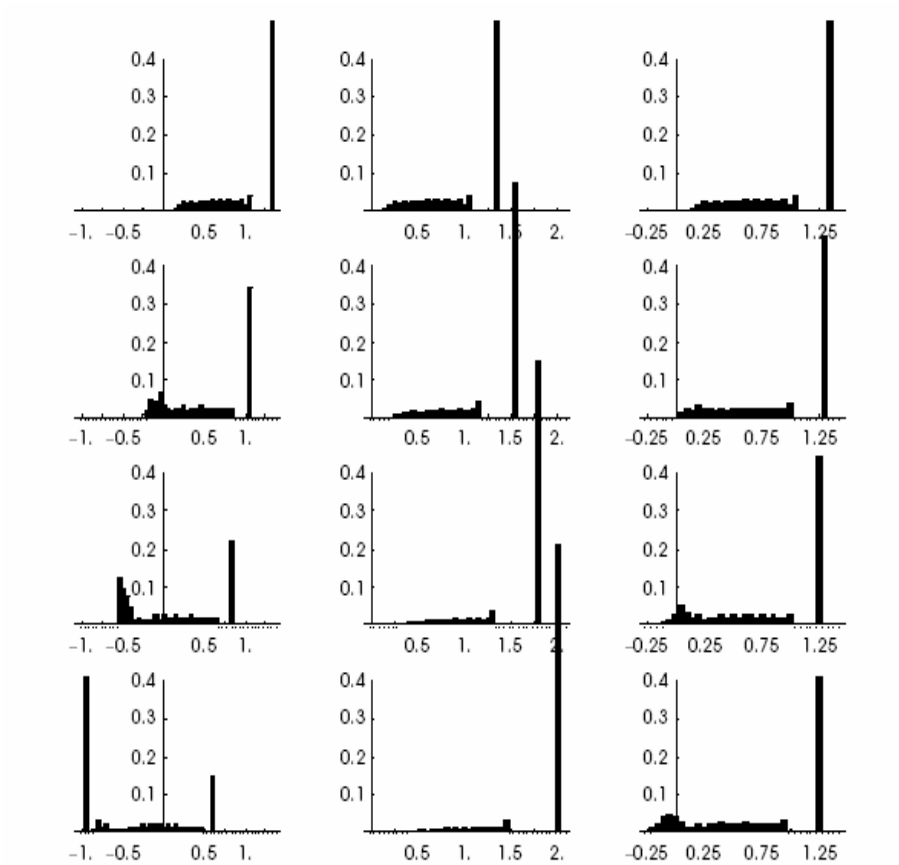
Transition from weak-strong to strong-strong regime at intensity ratio ~0.6:





Simulation by the Hybrid Fast Multipole Method (Herr, Jones & Zorzano, 2001) confirms this conclusion obtained analytically (YA, 1996)

Multi-bunch modes



The Yokoya factor for LR interactions is ~2, so the gap between coherent and incoherent tunes may become larger.

The alternating crossing keeps it ~ unchanged.

Spectral density of π-oscillations vs. coherent tune shift, normalized by $\xi_x^{(head\text{-}on)}$, for one head-on and (from top to bottom) N_{LR} = 0, 4, 8, 12 long-range interactions at $d = 5\sigma_x$ separation in the case of horizontal (left), vertical (center) and alternating (right) crossing

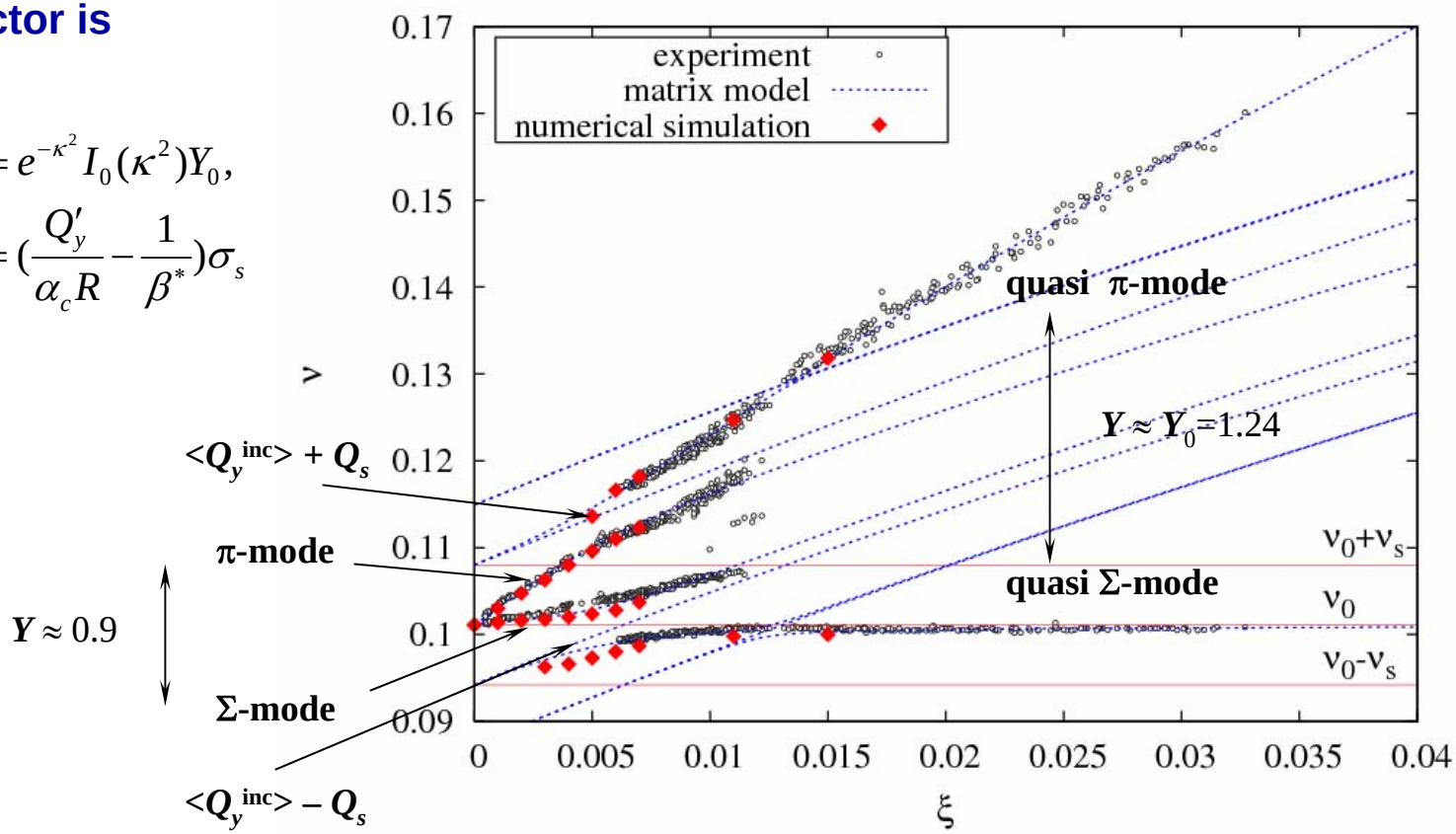
Synchro-betatron modes

At $\xi < Q_s$ the Yokoya factor is

$$Y = e^{-\kappa^2} I_0(\kappa^2) Y_0,$$

$$\kappa = \left(\frac{Q'_y}{\alpha_c R} - \frac{1}{\beta^*}\right)\sigma_s$$

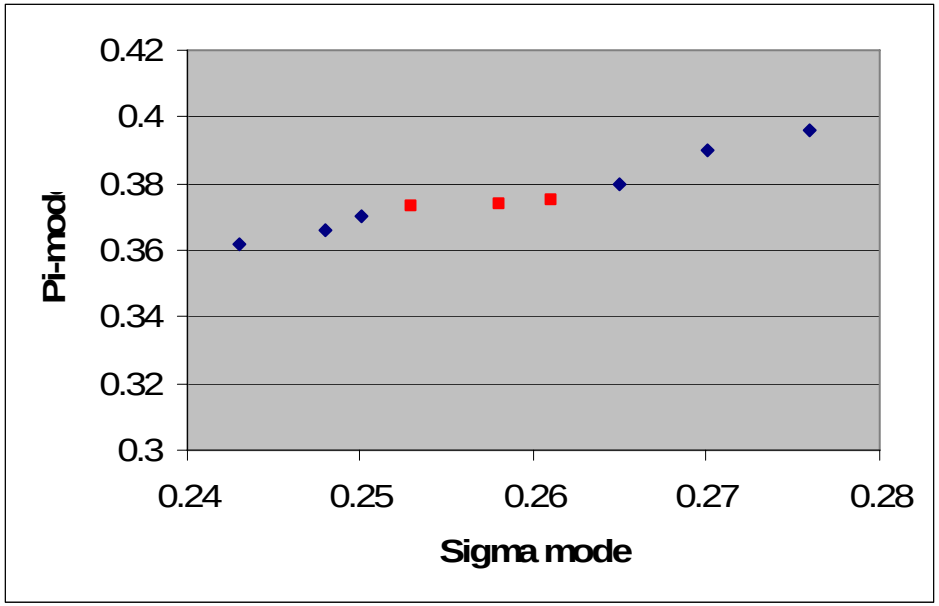
VEPP-2M



Measured tunes (dots) of vertical oscillations of one *e*+ and one *e*- bunches colliding at two IPs in VEPP-2M as functions of the beam-beam parameter/IP; Q_y= 3.101, Q_s = 0.007, σ_s = 3.5cm, β^* = 6cm.
Red diamonds: simulations with Beam-Beam-3D (A.Valishev, J.Qiang, E.Stern)

BB-driven coherent instability

Coherent beam-beam resonance (LEP)



Spontaneous excitation of π-mode observed in LEP (courtesy of K.Cornelis)

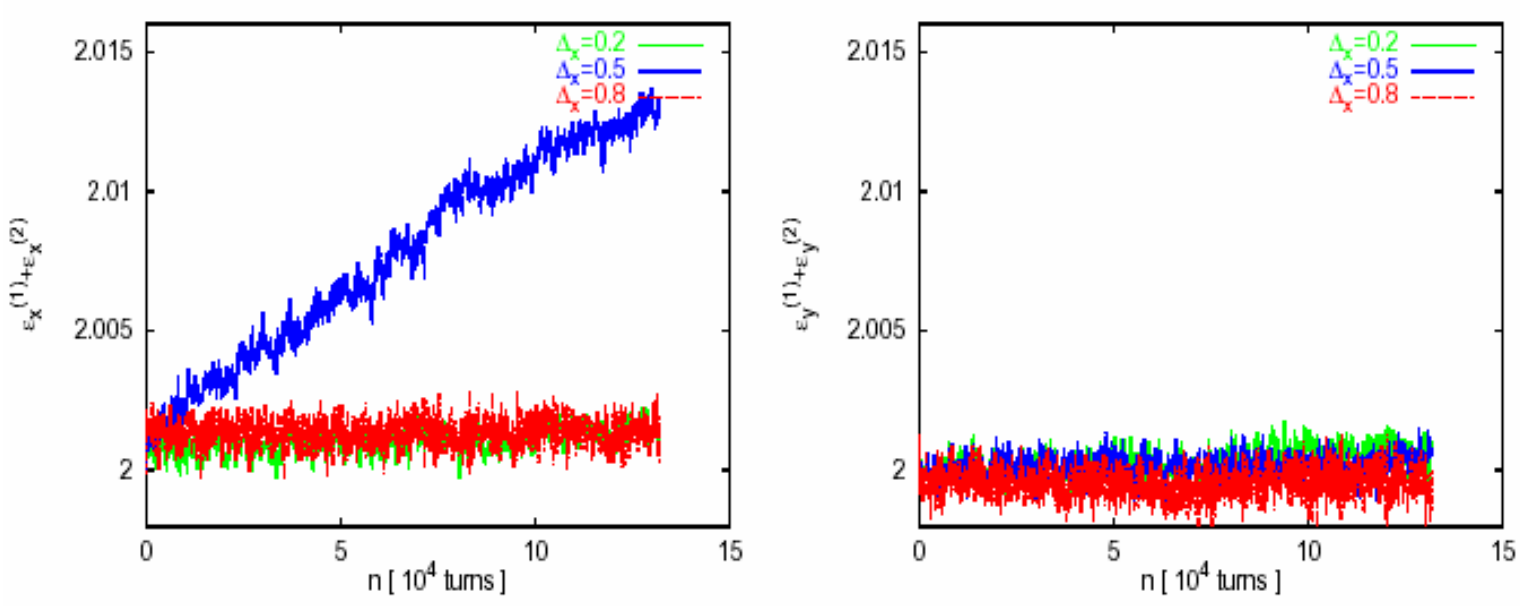
Explained (YA, 1999) by coupling of dipole π-mode $\nu = \nu_0 + 1.33\xi$

to quadrupole Σ-mode due to an offset $2\nu \approx 2\nu_0 + \xi$

$$\nu_0 \approx \frac{n}{3} - \frac{1+1.33}{3}\xi_x \approx .256 \quad \text{at} \quad \xi_x = 4\times 0.025 = 0.1$$

BB-driven coherent instability

Coherent beam-beam resonances of high order can be dangerous with specific choice of the working points:



Tracking simulation (soft-Gaussian model) of the quadrupole-octupole resonance $4Q_{x1}+2Q_{x2}$ at different tunes Q_{x1} =.31, Q_{x2} =.385 of the LHC beams (M.-P. Zorzano, 2000).

Impedance-driven coherent instabilities

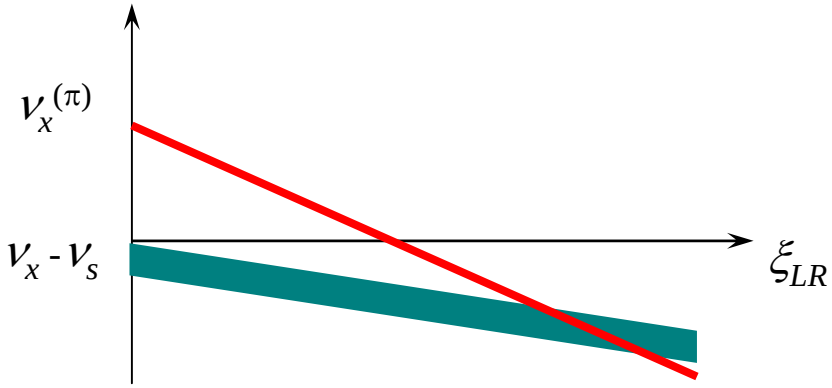
Lack of Landau damping or even aggravation of coherent instabilities by beam-beam interaction has been observed in many machines:

- **Lowering the TMCI threshold by LR interaction in LEP 8+8 operation**
- **Instability in the Tevatron at low chromaticity**
- **Instability in RHIC in the end of Cu injection**

TMCI in LEP 8× 8 operation

- **threshold at injection ~30% lower for 8× 8 than for 4× 4 bunches**
- **tentative explanation: ~ twice larger tuneshift of the coherent π-mode (YA, 1996)**

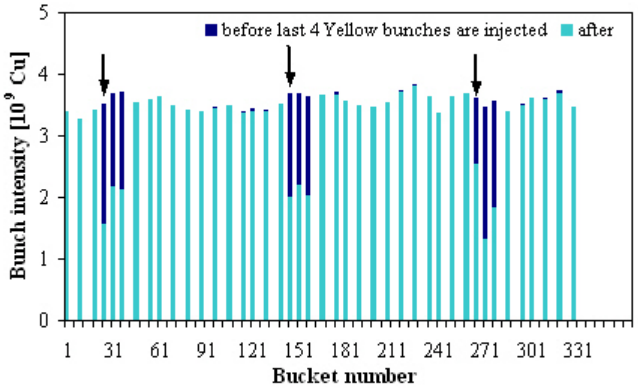
(***another possibility: larger impedance seen on pretzel orbits***)

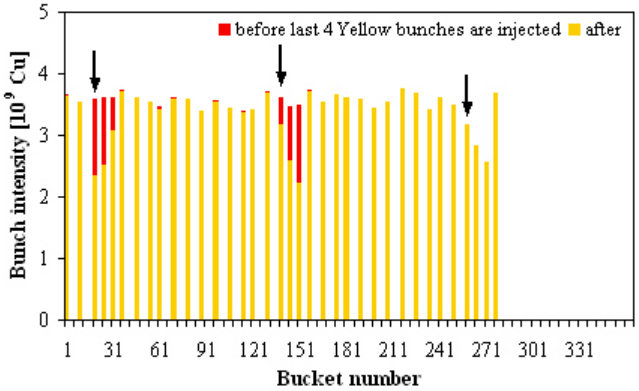


Long-range interaction "sponsoring" TMCI

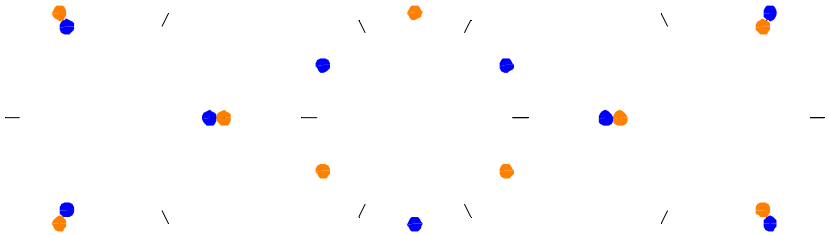
Instability in RHIC during Cu injection

On many occaisions during Cu+Cu run instability occur at the end of injection in the Yellow ring:



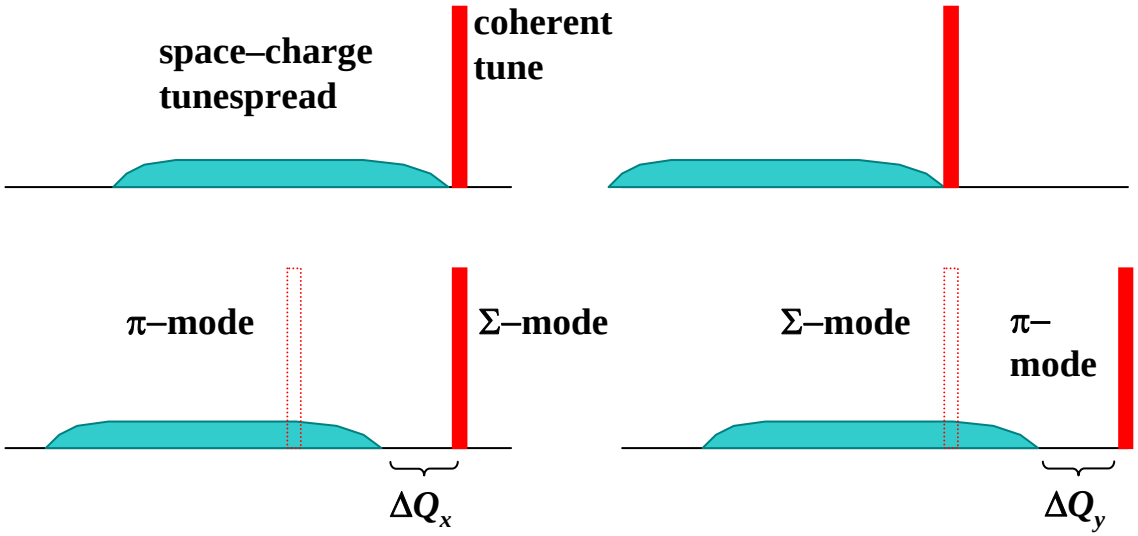


Loss pattern in the result of instability (courtesy of W.Fischer)



Long-range interaction at 6 crossing points couples sets by 3 bunches in each beam

Instability in RHIC during Cu injection

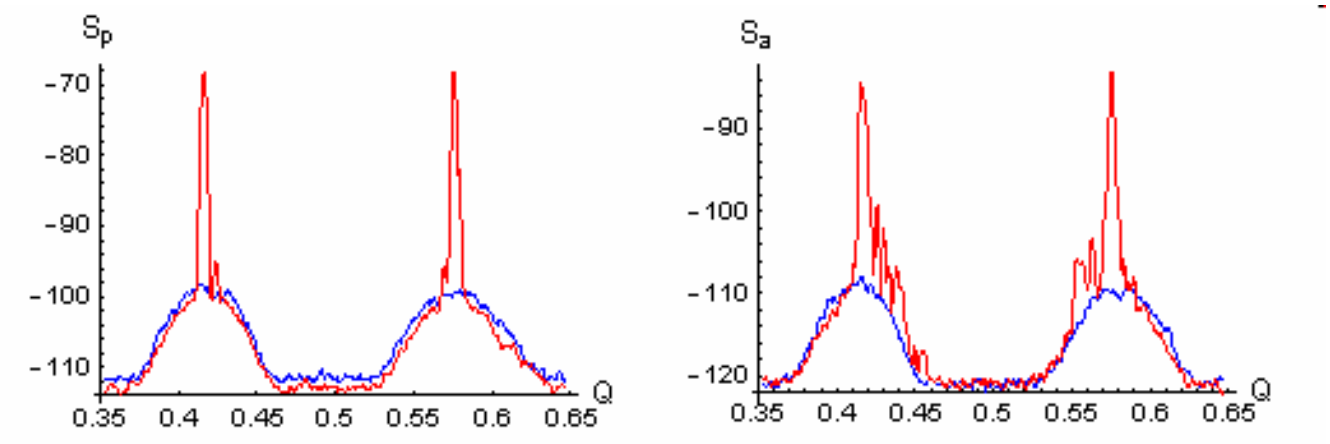


Tentative explanation of the instability in RHIC as loss of Landau damping by the space-charge tunespread due to coherent beam-beam tuneshift

Instability of colliding beams in the Tevatron

Dedicated end-of-store experiment (N_p=2·10^{11}, N_a=2·10^{10}) on 04/21/05:

- **vertical chromaticity lowered from 10.5 to 2.5 units**
- **chromaticity lowered from 7 to 1.5 units -> beams went unstable**
- **Tev quenched due to pbar losses**

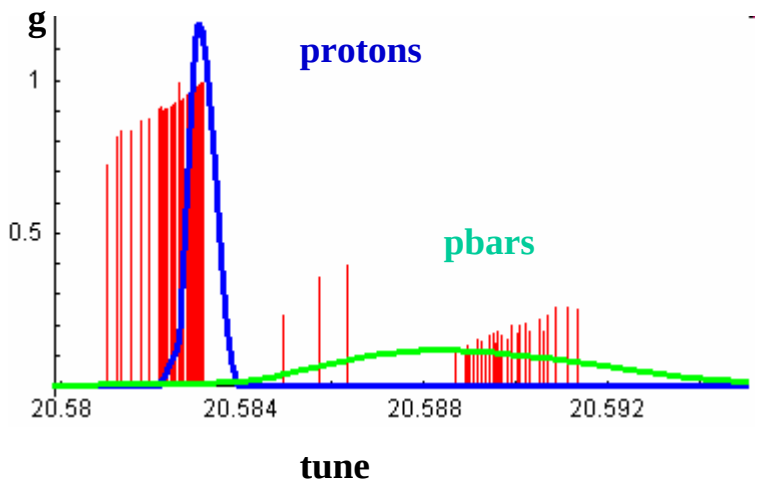


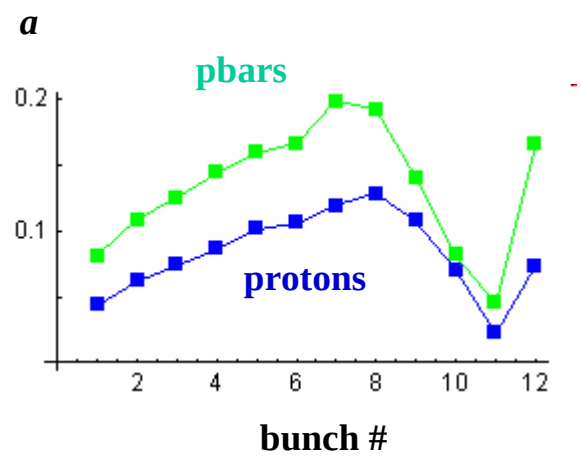
1.7GHz Schottky spectra in the proton (left) and antiproton (right) beams before the onset of instability (blue) and just before the quench (red) (data provided by A. Jansson)

- **Beam-beam tunespread failed to provide Landau damping**
- **Pbars had a factor of 4 larger amplitude, very much in line with the rigid-bunch model predictions (see the next slide)**

Instability of colliding beams in the Tevatron

The Yokoya factor for LR interactions $Y = \Delta Q_{coh} / \xi = 2$, therefore multiple LR interactions can switch off Landau damping





Growth rates of multibunch modes in Tevatron (red lines) and spectral functions of the proton and pbar beams, $N_a / N_p = 0.1$, $Q_a = 20.577$, $Q_p = 20.582$, $\xi = 0.02$

Amplitudes of proton and pbar bunches vs. the bunch position in the train for mode #2 from the left plot.

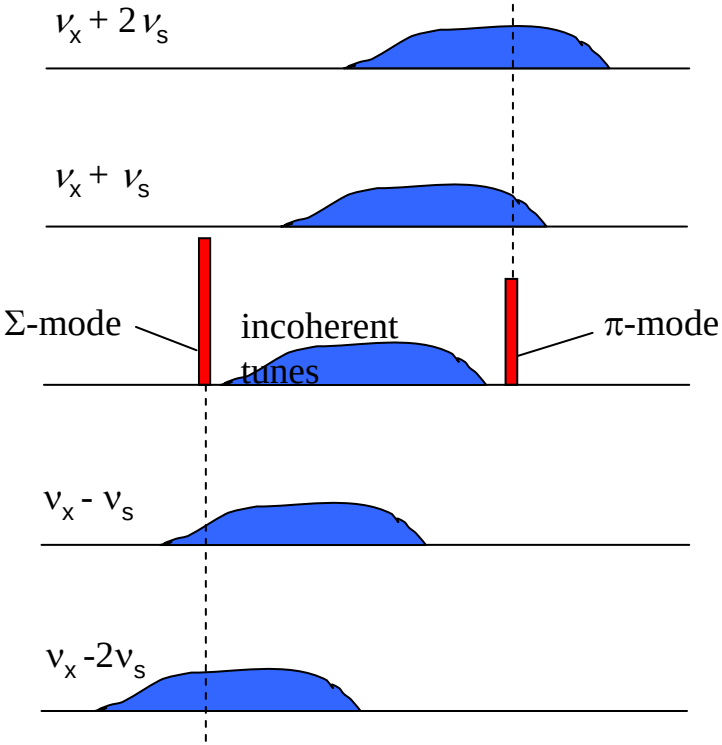
- **there is a number of modes with tunes far from the proton tunespread but with growth rates almost as high as in the proton beam alone**
- **antiprotons participate in oscillations with larger amplitude**
- **their intensity may be not sufficient to suppress the instability**

Cures

- **Several methods of suppression of discreet modes in LHC proposed:**
  - **Splitting bare lattice tunes (A.Hoffman)**
  - **Redistribution of phase advances between IPs (A.Temnykh, J.Welch)**
  - **Different parity of integer parts of the tunes in separate rings (W.Herr)**
- **Transverse dampers (pickup noise <1μm required)**
- **Head-tail damping of dipole oscillations by positive chromaticity**
- **Landau damping by overlapping synchro-betatron sidebands**

Coupling to synchro-betatron sidebands is determined by parameter

$$\kappa^2 = \left(\frac{Q'_x}{\alpha_c R} - \frac{1}{\beta^*}\right)^2 \sigma_s^2$$



Effects of finite bunch length and chromaticity

Theory predicts interference between the last two effects:

- **strong beam-beam interaction ($\xi > Q_S$) modifies the head-tail damping so that it cease to depend on chromaticity**
- **positive chromaticity can switch off Landau damping by sidebands if**

$$Q'_x \approx \alpha_M R / \beta^* \approx 3 \quad \text{in LHC}$$

- **conversely, negative chromaticity will increase coupling to sidebands and enhance Landau damping w/o weakening the head-tail damping**

The first prediction agrees with observations in the Tevatron Run I (FERMILAB-TM-1970, 1996) where allegedly it was possible to make chromaticity negative in collision though no records in the logbook were found.

As shown earlier it is not possible in Run II, probably due to large LR contribution.

These effects are both interesting and important, still awaiting confirmation by simulations and experiments.

Nonlinear BB compensation with e-lenses

Common sense suggests that reduction in the tunespread will make the beams less stable, however:

- **the principal difficulty expected is that incoherent beam-beam tunespread does NOT overlap coherent spectral lines anyway;**
- **Landau damping by synchrotron sidebands requires that the center of the sideband was close to the coherent line, i.e.**

$$Q_s + \frac{1}{2}\xi \approx Y\xi \Rightarrow$$

$$\xi \approx Q_s/(Y - 1/2) \approx .0021/.7 = .003 \quad \text{in LHC}$$

- **increased particle density in the tune space will enhance the damping effect of the sidebands (provided the overlap criteria are satisfied).**

Nonlinear BB compensation can fix problems with both incoherent and coherent BB effects, but more studies are necessary