“Discussion of Synchro-Betatron Resonances”

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SLAC, Stanford University

Plenary: Beam-Beam

June 14, 2006

Synchro-Betatron resonance

Coupling between transverse and longitudinal oscillations may lead to additional resonances (satellites) that satisfy the relation

$$kQ_x + lQ_y + mQ_s = n$$

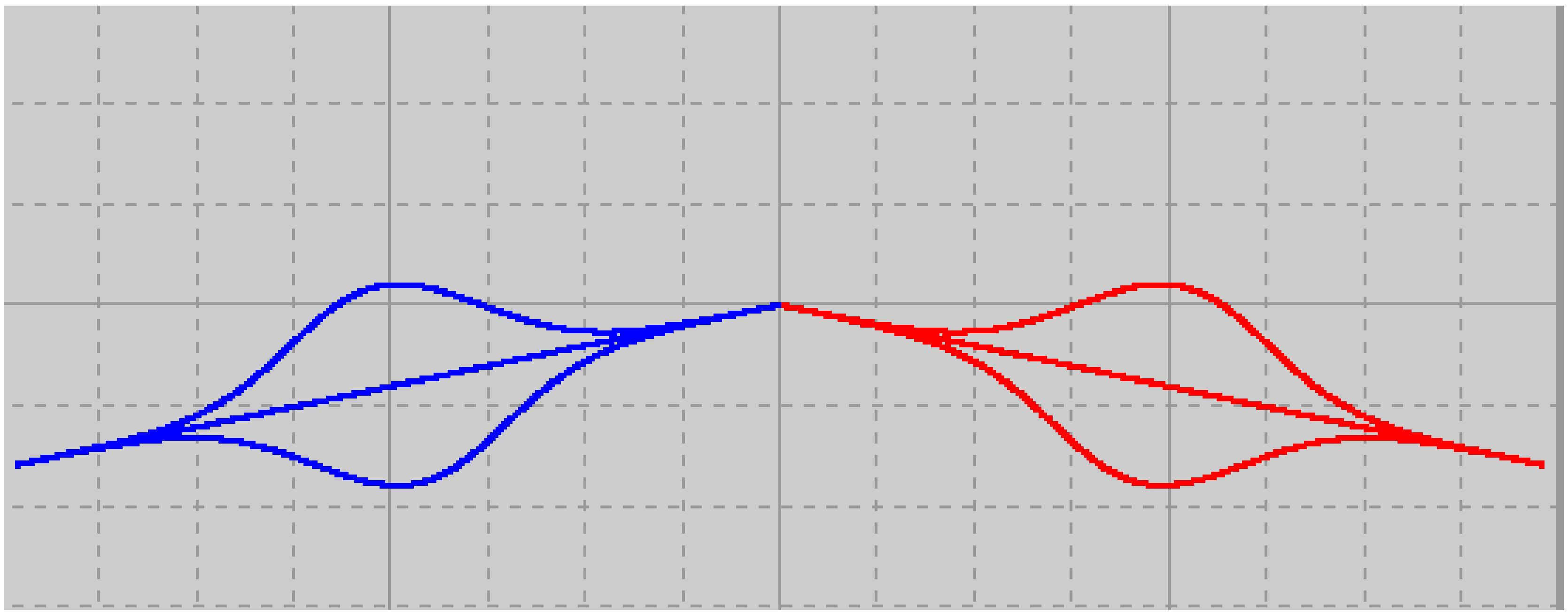
$Q_x \quad Q_y$ are betatron frequencies

Q_s is synchrotron frequency

k, l, m, n are integers

Collision at a large angle

☆ *press the window to play movie*



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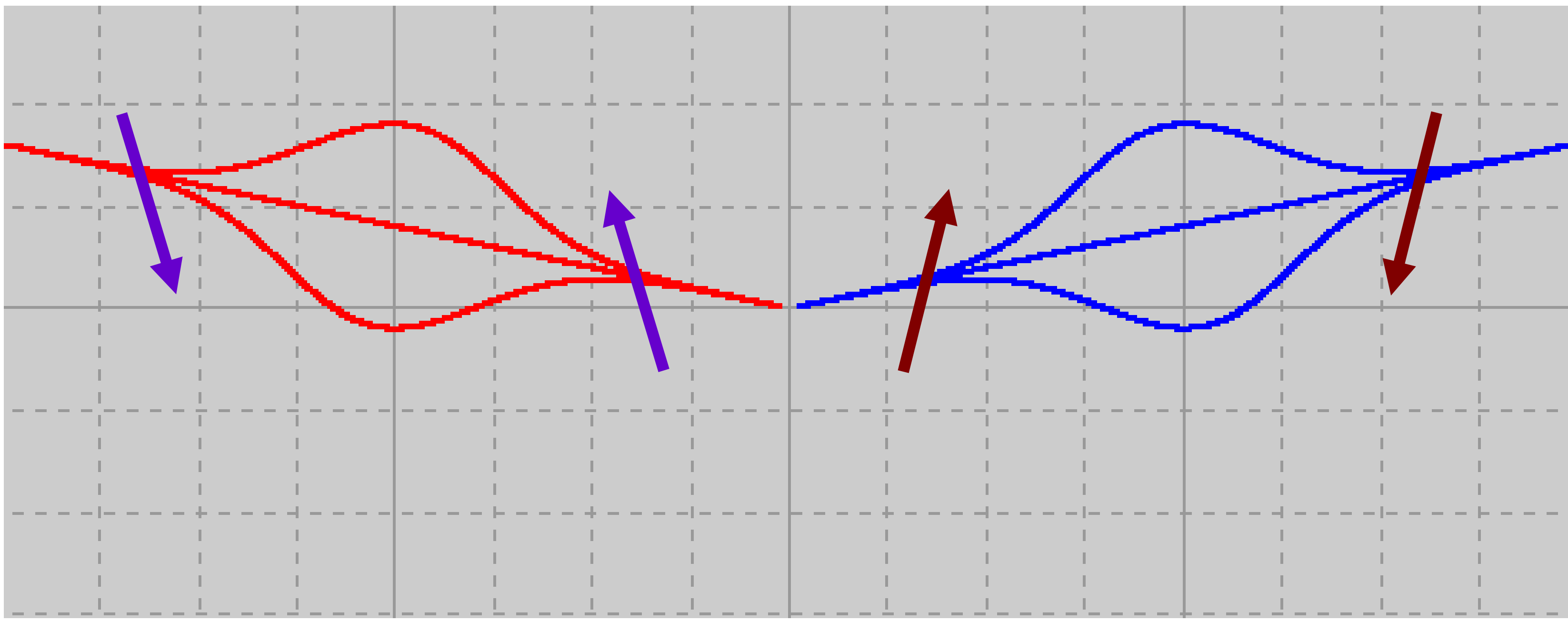
Kicks for head and tail



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Trajectories over a colliding bunch

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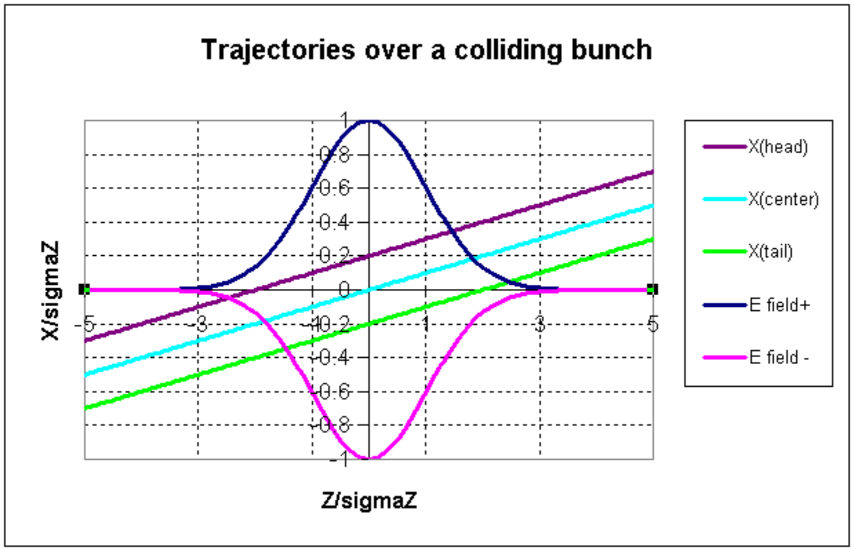


Trajectory equation

$$x = (x_\beta + s * tg\phi) + z * tg\varphi$$

Total kick

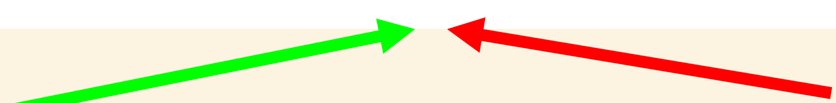
$$\Delta\vec{p} = \int \vec{F}(x(z), z)dz$$

For symmetrical bunches

$$\Delta\vec{p} = \int \vec{F}(x = x_\beta + s * tg\phi, z)dz$$

Angle kick

- When Head-on kick focuses the bunch in X-direction
- Angle kick additionally rotates the bunch focusing particles in Z-direction



Coupling at a crossing angle.

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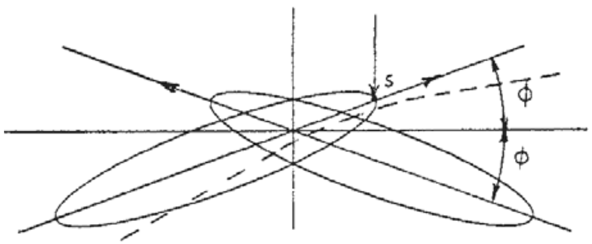

Fig. 1: Orbit distortion due to a crossing angle

A.Piwinski
DESY 77/18
1977

Transverse kick (D_x=0) at total angle 2ϕ

$$\partial x'_\beta = f(x_\beta + \phi z)$$

$$\partial p_z = \phi * \partial p_x$$

$$\frac{\partial E}{E} \approx \frac{\partial p}{p} \approx \frac{\partial p_z}{p} \approx \phi \frac{\partial p_x}{p} = \phi * \partial x'_\beta = \phi * f(x_\beta + \phi z)$$

linear coupling for small oscillations

$$f(x_\beta + \phi z) = -\frac{4\pi\xi_x}{\beta_x^*}(x_\beta + \phi z)$$

The phases of the egenvalues

$$\sigma_{x,eff} = \sqrt{\sigma_x^2 + \phi^2 \sigma_z^2}$$

$$\xi_x = \frac{r_0 N_b \beta_x^*}{2\pi\gamma\sigma_{x,eff}\left(\sigma_{x,eff} + \sigma_y\right)}$$

$$\mu_1 = \mu_x + 2\pi\xi\left(1 \pm \phi\sqrt{\frac{-\alpha_p C}{\beta_x^* \sin\mu_x}}\right)$$

$$\mu_2 = \mu_s - 2\pi\xi\phi\left(\frac{\alpha_p C}{\beta_x^* \mu_s} \pm \phi\sqrt{\frac{-\alpha_p C}{\beta_x^* \sin\mu_x}}\right)$$

Rise times for the first modes

when $\sin\mu_x > 0$

$$\tau_{1,x} = \frac{1}{2\pi\xi\phi}\sqrt{\frac{\beta_x^* \sin\mu_x}{\alpha_p C}}$$

$$\tau_{2,s} = \frac{1}{2\pi\xi\phi^2}\sqrt{\frac{\beta_x^* \sin\mu_x}{\alpha_p C}}$$

Super-B, angle tune shift

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$$\sigma_{x,eff} = \sqrt{\sigma_x^2 + \phi^2 \sigma_z^2}$$

$$\xi_x = \frac{r_0 N_b \beta_x^*}{2\pi\gamma\sigma_{x,eff}\left(\sigma_{x,eff} + \sigma_y\right)}$$

$$\Delta\mu_x = \pm 2\pi\xi\phi\sqrt{\frac{-\alpha_p C}{\beta_x^* \sin\mu_x}}$$

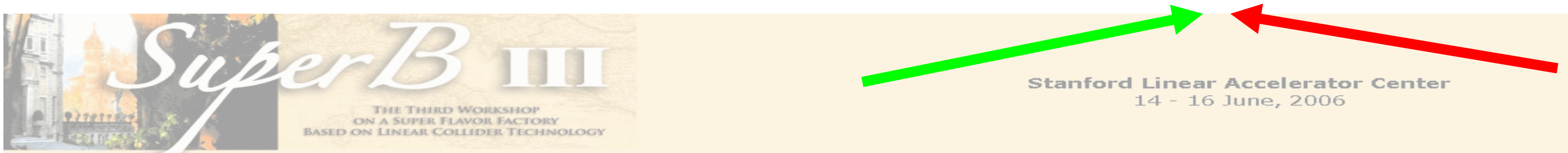
$$\Delta\mu_s = \Delta\mu_x * \phi$$

$E_1 =$	4	Gev
$E_2 =$	7	GeV
$\gamma_1 =$	7827.7886	
$\gamma_2 =$	13698.63	

2.82E-13	cm	2.82E-12	mm

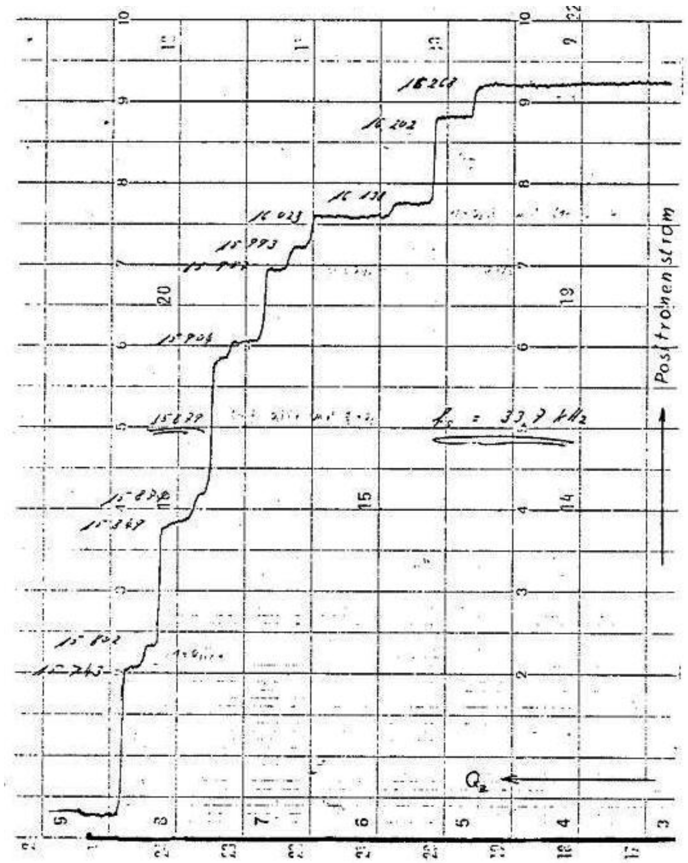
$\phi =$	25.00	mrad	0.025	rad
$N_b =$	4.00E+10		4.00E+10	
$\beta_x^* =$	9.000	mm	9.00	mm
$\sigma_y =$	0.013	mkm	1.30E-05	mm
$\sigma_x =$	2.700	mkm	2.70E-03	mm
$\sigma_z =$	6.000	mm	6.00	mm
$\alpha_p =$	0.001		0.001	
$C =$	6.000	km	6.00E+06	mm
$\mu_x =$	0.510		3.20442451	rad
$\mu_s =$	0.010		0.06283185	rad
$\sigma_{x,eff} =$	150.024	mkm	1.50E-01	mm
$\xi_x =$	0.000916	*2pi=	5.75E-03	
$\Delta\mu_x =$	1.48E-02			
$\Delta\mu_s =$	3.71E-04			
$\frac{\Delta\mu_x}{2\pi\xi_x} =$	2.58			

"Angle" tune shift is 2.5 times higher than "head-on" tune shift



Satellites at DORIS

Experimental result for beam-beam interaction at a crossing angle of 2*12 mrad



Beam losses as a function of the vertical betatron frequency

25 vertical betatron resonances were observed

$6 + 3Q_s$, $6 + 4Q_s$

$49/8$, $(49 + Q_s)/8$, $(49 - 2Q_s)/8$

$43/7$, $(43 \pm Q_s)/7$, $(43 - 2Q_s)/7$

$37/6$, $(37 - Q_s)/6$, $(37 - 2Q_s)/6$

$31/5$, $(31 \pm Q_s)/5$, $(31 - 2Q_s)/5$, $(31 \pm 3Q_s)/5$, $(31 \pm 4Q_s)/5$

$25/4$, $(25 - Q_s)/4$, $(25 - 2Q_s)/4$

$28 - 3Q_x$, $Q_x - 1 - Q_s$

Lifetime on a resonance was between a few second and 15 minutes.
The width of some resonances was about 5×10^{-4}

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General Synchro-betatron resonance properties (from PETRA experience)

- **Increase of beam dimensions and reduction of life time**
  - The transverse bunch dimensions can be enlarged by several standard deviations and the lifetime can be reduced to a few seconds
- **Strong dependence on a single bunch current**
  - Most of the resonances show a strong dependence on the single bunch current (bun not on the total current). With decreasing current goes asymptotically to a residual current

Synchro-betatron resonance properties

- **Constant short life time on** $Q_{x,y} - 2Q_s = n_{x,y}$
  - These satellites have a short life time (a few seconds) even for very small currents, and the residual current is zero. This is observed in a low betta optics but is not found in an injection optics
- **Strong dependence on orbit position**
  - All satellites show a strong dependence on orbit position, but the orbit position with minimum satellite strength usually differs from the orbit obtained by automatic orbit correction

Synchro-betatron resonance properties

- **Energy dependence**
  - All current dependent satellites are weaker at higher energy, but for the satellite

$$Q_{x,y} - 2Q_s = n_{x,y}$$

    the residual current is zero also at 18GeV
- **No dependence on chromaticity and feedback**
  - Strong influence on bumps in interaction region having large amplitudes in the large quadrupoles.

Study at Cornell CESR

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Beam-beam interaction with a horizontal crossing angle

D. L. Rubin, M. Billing, J. Byrd, T. Chen, Z. Greenwald, D. Hartill, J. Hylas, J. Kaplan, A. Krasnykh, R. Meller, S. Peck, T. Pelaia, D. Rice, D. Sagan, L. A. Schick, J. Sikora and J. Welch
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York, USA

NIM A330
pp.12-20
1993

We report measurements of the dependence of luminosity and beam-beam tune-shift parameter on horizontal crossing angle at a single interaction point in the Cornell Electron Storage Ring. The report is based on data collected between September 1991 and January 1992 at CESR. For head-on collisions (zero crossing angle) the achieved tune-shift parameter is $\xi v = 0.03 \pm 0.002$ at 11 mA/bunch. For a crossing half-angle of $\theta c = \pm 2.4$ mrad, we achieve $\xi v = 0.024 \pm 0.002$ at similar bunch currents. The data suggest some degradation of performance if the trajectory through the interaction region is distorted magnetically even while head-on collisions are preserved. Therefore at least some of the observed dependence of tune-shift parameter on crossing angle may be due to the associated large displacement of the beam trajectories in the interaction region optics. Furthermore, with the introduction of the crossing angle, the algorithm for optimizing luminosity is significantly complicated due to linear optical errors and the solenoid compensation. We interpret the measured tune-shift parameter at $\theta c = 2.4$ mrad as a lower limit to what can ultimately be achieved.

1/5 satellite at Cornell

PHYSICAL REVIEW E VOLUME 49, NUMBER 3 MARCH 1994

Nonlinear coupling in the crossing-angle beam-beam interaction

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(Received 8 March 1993; revised manuscript received 16 July 1993)

The effects of the beam-beam interaction with a small crossing angle on large-amplitude particles in an e^+e^- collider are studied. An analytical resonance analysis method is developed to understand the nonlinear coupling resonance driving mechanism. The major effect of the crossing angle for large-amplitude particles is to drive the $5Q_x \pm Q_s$ = integer resonance family. The analytic results are consistent with a computer simulation. The resonance is observed in the crossing-angle experiment in the Cornell Electron Storage Ring.

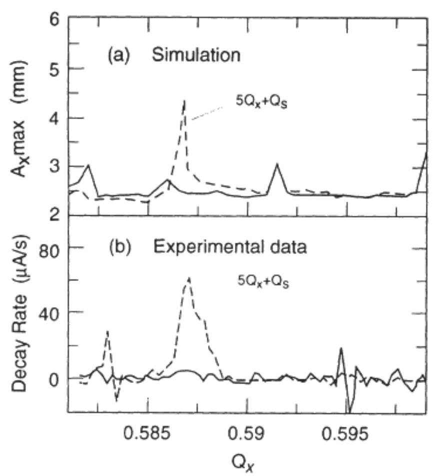

FIG. 6. (a) Simulation result, maximum amplitude vs horizontal tune. (b) Experimental data, decay rate as a function of horizontal tune. Solid lines are the head-on collision data, and dashed lines are the crossing-angle data.

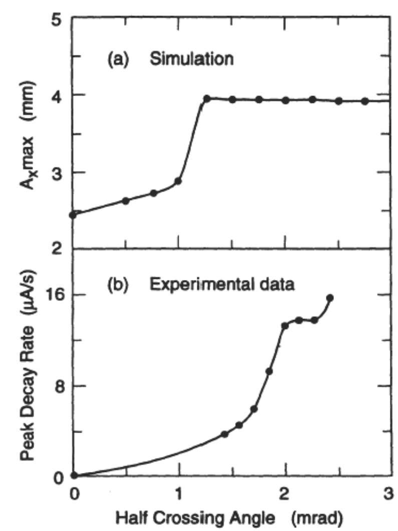

FIG. 8. Resonance strength as a function of crossing angle. (a) Maximum amplitude on the resonance vs crossing angle. (b) Peak decay rate on the resonance vs crossing angle.

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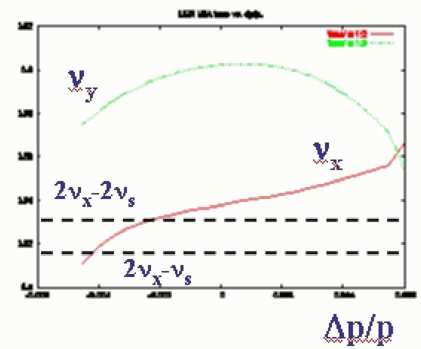
PEP-II (Simulations)

PEP-2 LER Dynamic Aperture Simulation

- Single beam dynamic aperture versus tune and $\Delta p/p$.
- Realistic MIA machine model, $\beta^* = 36 / 0.8$ cm.
- Tune space near half-integer is limited by resonances, especially $2\nu_x - n\nu_s$, and chromatic tune spread.
- Best aperture at tunes $.522 < \nu_x < .530$, $\nu_y > .574$.
- Better compensation of the 2nd order chromatic ν_y tune shift is needed.

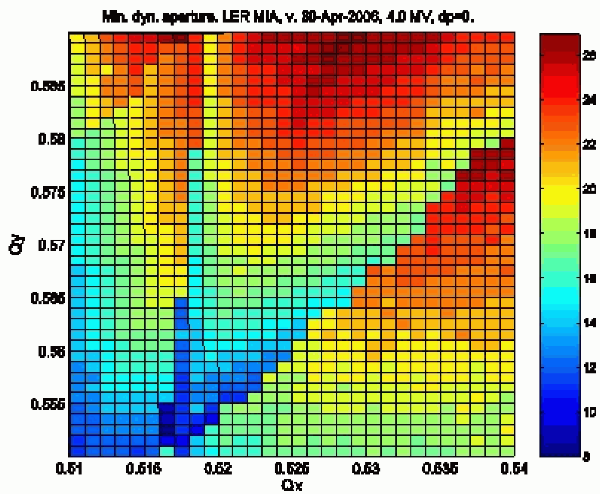


Beam Dynamics

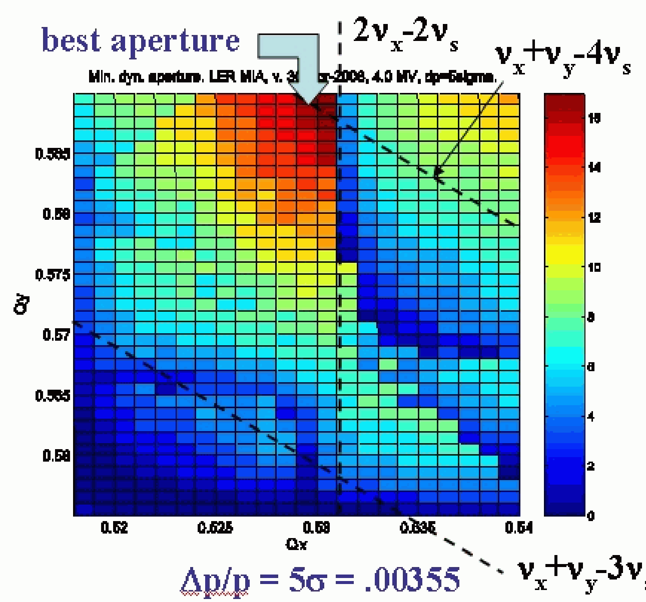
Yunhai Cai

June 7, 2006

DOE review



> 10σ aperture at $\Delta p/p = 0$



$\Delta p/p = 5\sigma = .00355$

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PEP-II: Luminosity and tunes from Tune Monitor

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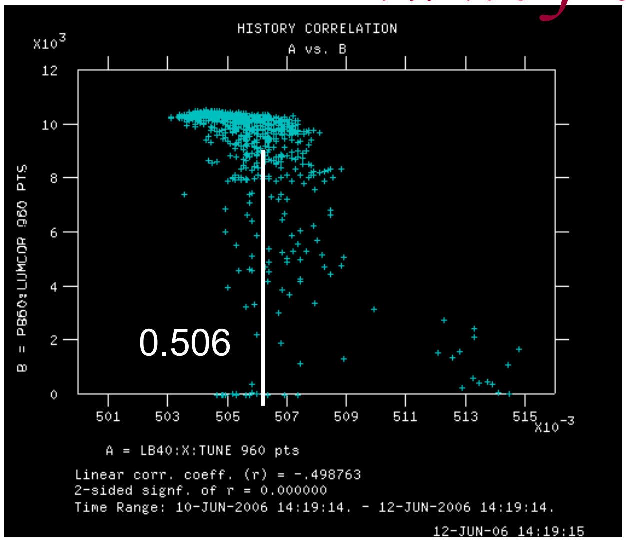
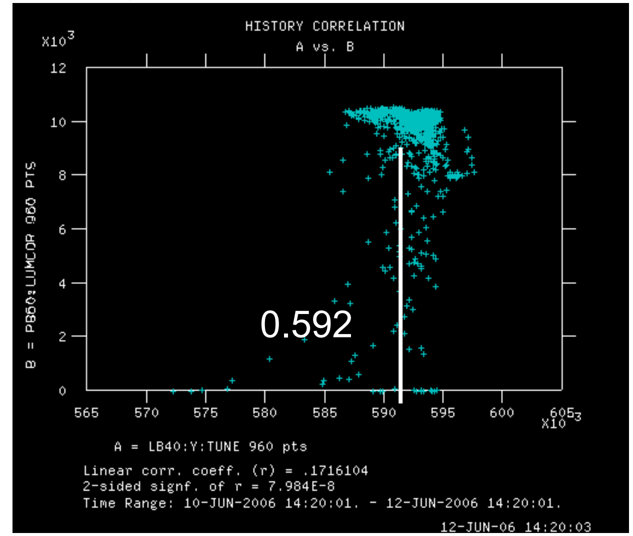
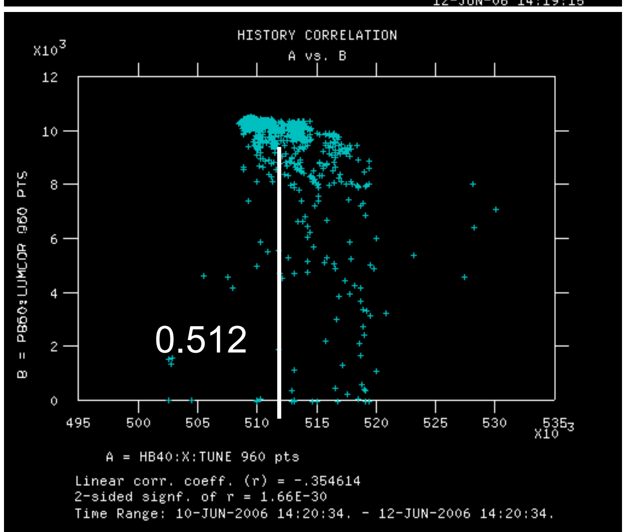
LER Qx



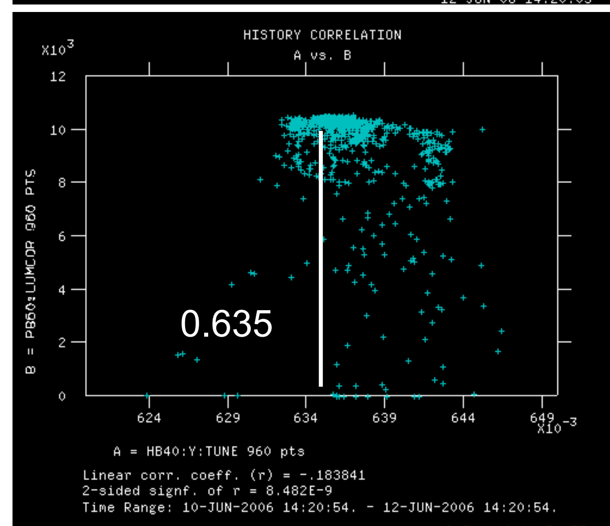
LER Qy



HER Qx



HER Qy



PEP-II. Only LER during coast running

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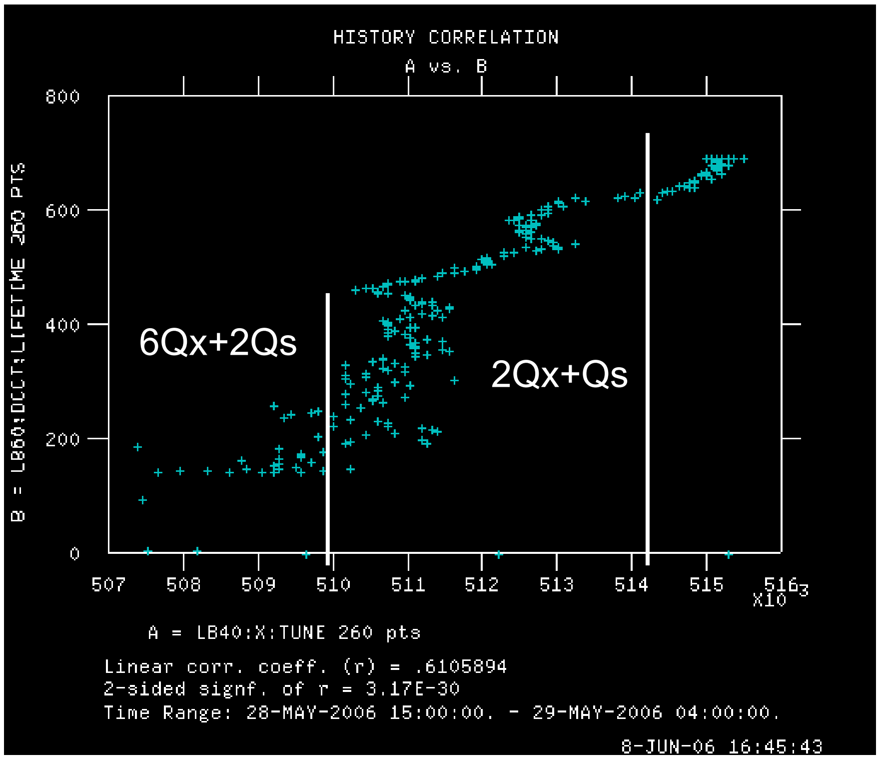
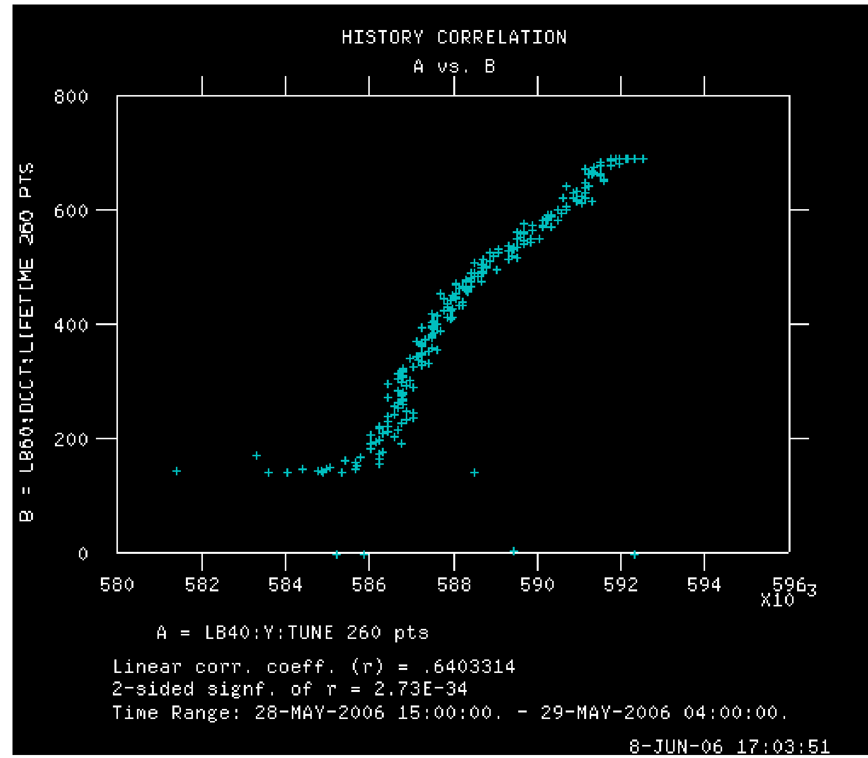


Qx



Qy

Kohji Hirata: "Don't Be Afraid…"

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SLAC–PUB–6375
July 1994
(A)

Don't Be Afraid of Beam-Beam
Interactions
With a Large Crossing Angle*

Kohji HIRATA†

VOLUME 74, NUMBER 12 PHYSICAL REVIEW LETTERS 20 MARCH 1995

Analysis of Beam-Beam Interactions with a Large Crossing Angle

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(Received 25 October 1993)

The beam-beam interaction for a flat beam with a large horizontal crossing angle is studied for the case in which the vertical betatron function at the interaction point is comparable to the bunch length. It is shown that crossing with a large angle has less serious detrimental effects than is usually believed. A large crossing angle might have several merits for future high-luminosity colliding rings.

†Leave from KEK, National laboratory for High Energy Physics, Tsukuba, Ibaraki 305, Japan.

Submitted to Physical Review Letters

Kohji Hirata simulations

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For the value $\eta_{x,y} = 0.01$ of the nominal beam-beam parameter, the beam sizes are shown in Fig. 2. For $\phi = 0$, the peaks indicate the resonances (from left to right) $n(\nu_x - \eta_x/2) + m(\nu_y - \eta_y/2) + l\nu_z =$ integer for $(n, m, l) = (0, 2, -1)$, $(0,2,-2)$, $(2,-2,-1)$, $(2,-2,0)$, $(0,4,0)$, $(2,2,0)$, $(2,2,-1)$, $(0,2,2)$, $(0,2,1)$, and $(0,2,0)$. Here $\nu_{x,y,z}$ are the tunes. For $\phi = 5$ mrad, the major difference is that $(1,2,0)$ and $(1,-2,0)$ appear. The latter two resonances are not SB resonances and are stronger for larger ϕ. These are induced by the nonlinear terms in $\mathcal{L}$ and $\mathcal{L}^{-1}$.

TABLE I. Standard parameters.

Emittances	(ϵ_x, ϵ_y)	$(2 \times 10^{-8}, 2 \times 10^{-10})$ m
Betatron functions at IP	(β_x^0, β_y^0)	$(1, 0.01)$ m
Bunch length	σ_z	0.01 m
Relative energy spread	σ_ϵ	10^{-3}
Tunes	(ν_x, ν_z)	$(0.2, 0.08)$
Damping times	(T_x, T_y, T_z)	(2000, 2000, 1000) turns

No satellites with a crossing angle!?

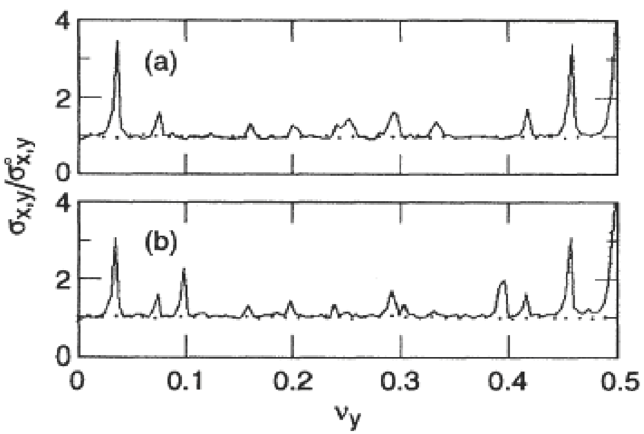

FIG. 2. σ_y/σ_y^0 (solid) and σ_x/σ_x^0 (dotted) vs ν_y for (a) $\phi = 0$ mrad and (b) $\phi = 5$ mrad, with $\eta = 0.01$.

The essential difference from Piwinski's formalism [1] is the inclusion of the bunch-length effects by using several slices. In fact, if we use only one slice, the effect grows almost proportionally to ϕ and does not decrease.

A.Piwinski angle

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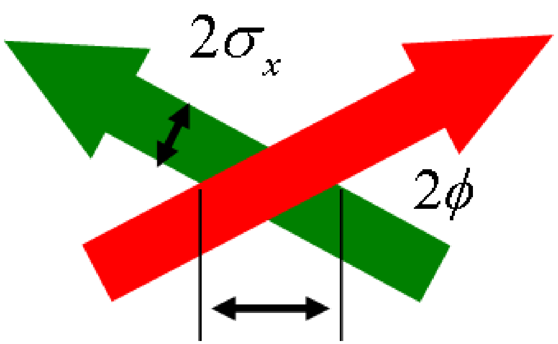

$$l_z = \frac{2\sigma_x}{\sin\phi}$$

A.Piwinski approach

$$f_{kick} \sim (x + \phi s)\rho_{bunch}$$

$$2\sigma_z < {l_z}/{2} \qquad \Phi_P = \frac{\sigma_z}{\sigma_x}\sin\phi < \frac{1}{2}$$

K.Hirata approach

$$f_{kick} \sim \frac{\delta}{\delta l_z}\rho_{bunch} \sim 0 \text{ (except head and tail)}$$

$$2\sigma_z > {l_z}/{2} \qquad \Phi_P = \frac{\sigma_z}{\sigma_x}\sin\phi > \frac{1}{2}$$

KEKB

Collision with finite crossing angle

K. Ohmi (KEK) for KEKB group

Beam-Beam Workshop 2003

20, May, 2003

Montauk, Long Island, NY

Summary

- KEKB achieved the luminosity 10^{34} $cm^{-2}s^{-1}$ with finite crossing scheme, 2x11 mrad.
- There was no serious problem for the crossing angle up to the beam-beam parameter of ~0.05.
- We were required fine tuning day by day.

Summary

- Collisions at a large crossing produce additional forces that rotate the bunch and focus particles in longitudinal direction.
- These forces may be responsible for synchro-betatron resonances in the ring
- X-tune shift may be several times lager than the shift according to classical “head-on” formula.
- More strong beam-beam simulations are needed to find the optimum tune spot