1. Nonlinear response of beam-beam system
2. HL-LHC crossing angle

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Collaboration of KEK-CERN crab cavity noise experiments
CERN-KEK collaboration for HL-LHC

LHC-CC11, CERN, 14-15 Nov. 2011

Force oscillation in nonlinear system

Duffing equation

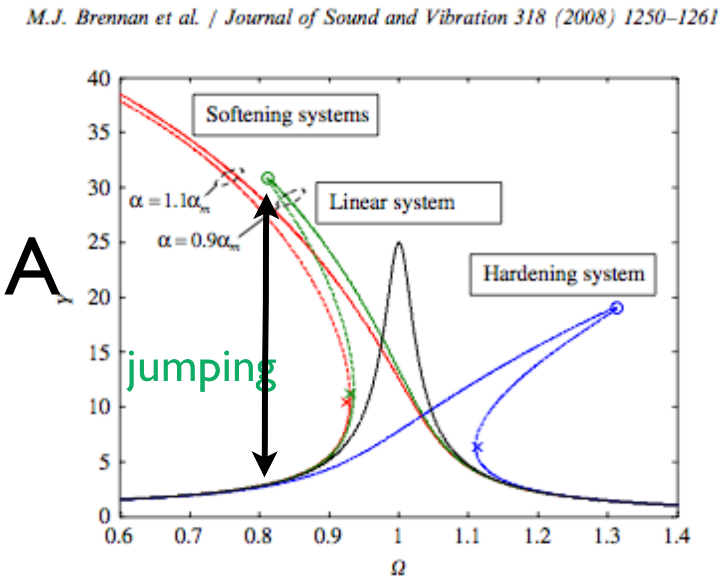
$$\frac{d^2x}{dt^2} - 2\alpha\frac{dx}{dt} + \omega_0^2 x - ax^3 = f\cos(\omega t + \varphi)$$

$$x = A\cos\omega t$$

A: Equilibrium amplitude

$$\left[\left(\omega_0^2 - \omega^2 - \frac{3a}{4}A^2\right)^2 + 4\alpha^2\omega^2\right]A^2 = f^2$$

M. Toda, Oscillation(振動論), 1968



- Jumping phenomenon
- Hysteresis

Jump phenomenon in Beam-beam system Ieiri and Hirata, PAC89

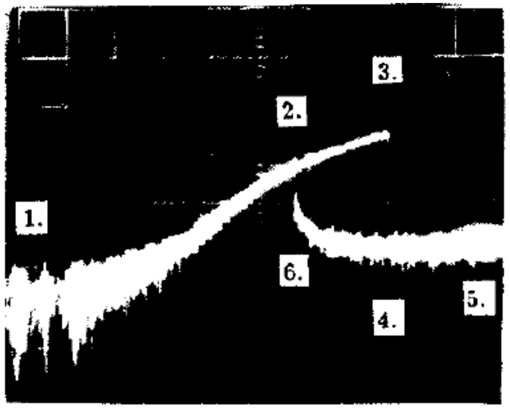


Figure 1. Hysteresis phenomena of the π-mode.

- Jump phenomenon was seen in beam oscillation response in colliding beams of TRISTAN.

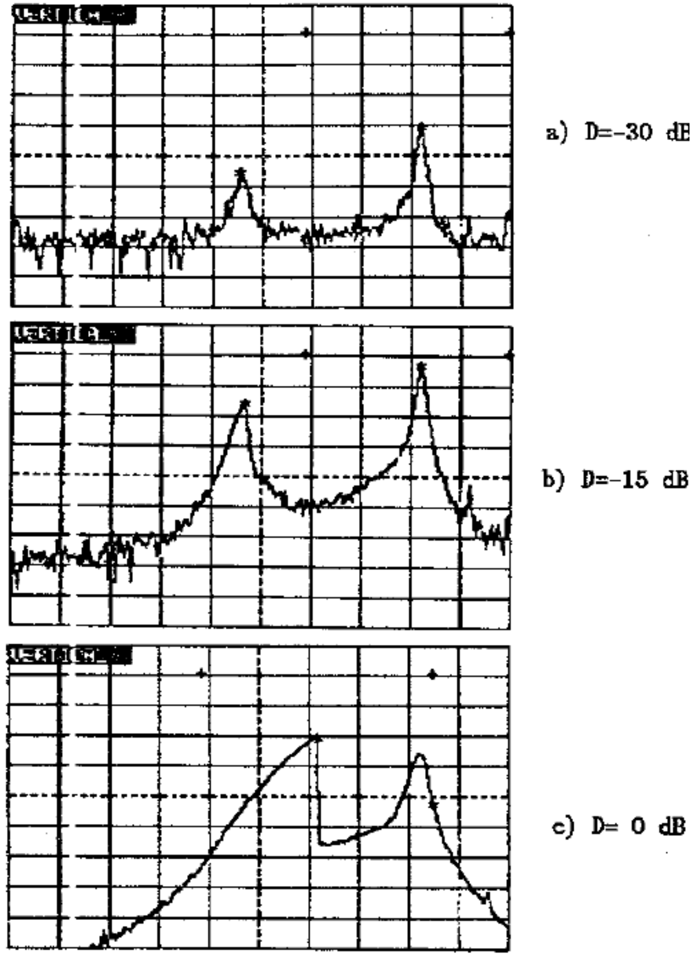
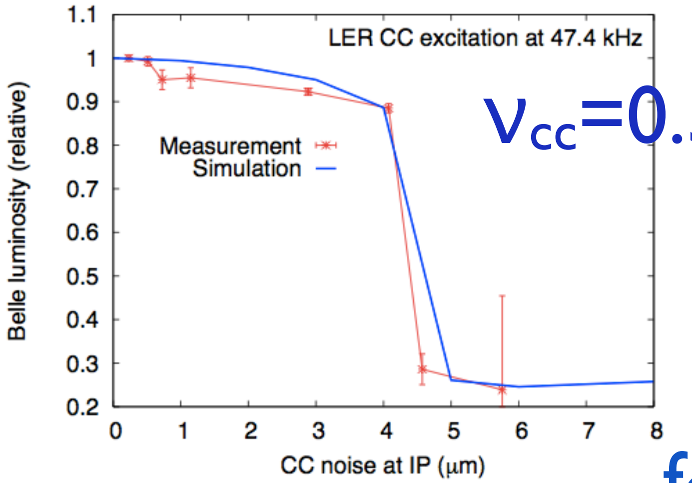
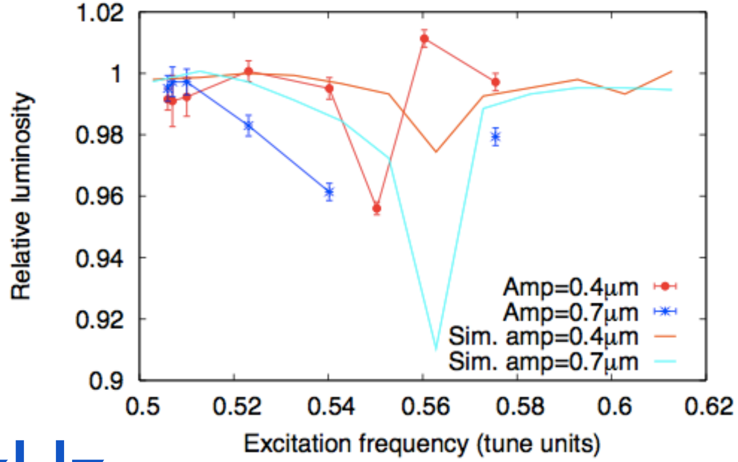


Figure 2. Resonant curves of the π- and the 0-modes with three relative deflector amplitudes, D=-30 dB, -15 dB and 0 dB. The right peaks show the 0-modes and the left the π-modes. The start frequency is 26 kHz and the stop is 41 kHz. The horizontal scale is 1.5 kHz/div. and the vertical is 5 dB/div.

Measurement of luminosity degradation due to harmonic excitation



ν_{cc}=0.526



f_0=100kHz

- Crab cavity phase noise is applied. Horizontal offset noise at the collision point is induced.
- Strong luminosity loss was observed at ν_{cc}=0.526 with strong excitation.
- Weak luminosity loss was observed at higher frequency.
- Dipole oscillation was seen at the luminosity drop.

Systematic study by strong-strong beam-beam simulation

- Macro-particles $N_p=N_e=200{,}000$
- 2D Particle in cell with longitudinal slice, $N_{sl}=7$.
- 3D beam-beam force, $F_z = -\dfrac{\partial \Phi(x,y;z)}{\partial z}$.
- Simulate 12,000 turns (radiation damping time=4000 turns)
- Harmonic excitation $\Delta p_x = k\cos(\nu_{cc}\omega_0 t)$.
- Feedback damping time 100 turns.

Beam-beam mode

- Linearized beam-beam transfer matrix times revolution matrix

$$M = KM_0$$

$$M_0 = \begin{pmatrix} \cos\mu_e & \sin\mu_e & 0 & 0 \\ -\sin\mu_e & \cos\mu_e & 0 & 0 \\ 0 & 0 & \cos\mu_p & \sin\mu_p \\ 0 & 0 & -\sin\mu_p & \cos\mu_p \end{pmatrix}$$

$$K = \begin{pmatrix} 1 & 0 & 0 & 0 \\ -4\pi\xi_e & 1 & 4\pi\xi_e & 0 \\ 0 & 0 & 1 & 0 \\ 4\pi\xi_p & 0 & -4\pi\xi_p & 1 \end{pmatrix} \qquad \mu_{e(p)} = 2\pi Q_{e(p)}$$

- Assuming no x-y coupling, the beam-beam modes are treated x-y independently.

- Horizontal motion is focus, because crab cavity induces horizontal excitation.

KEKB parameters

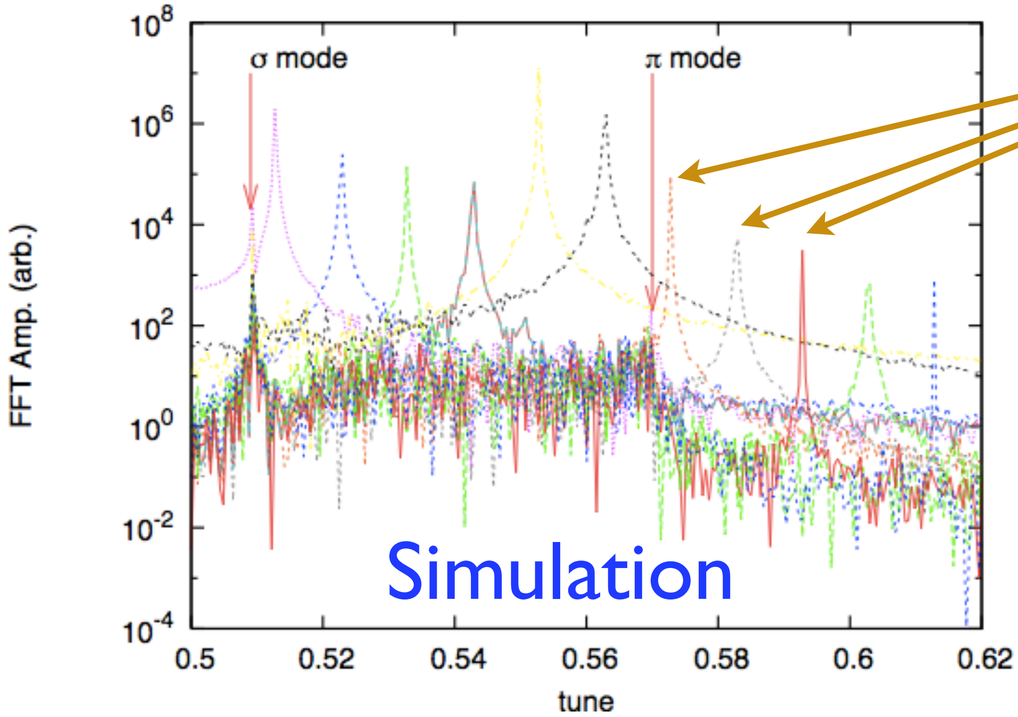
TABLE I: Machine parameters during the December 2008 crab cavity experiments in the KEKB.

	Unit	HER	LER
Particle		e^-	e^+
Particles per bunch	10^{10}	4.1	6.3
Number of bunches		100	100
Horizontal emittance (ϵ_x)	nm	24	18
Horizontal tune (Q_x)		44.507	45.512
Vertical tune (Q_y)		41.602	43.585
Horizontal beam-beam parameter (ξ_x)		0.100	0.111
Vertical beam-beam parameter (ξ_y)		0.077	0.099
Synchrotron tune (Q_s)		0.021	0.025
Revolution frequency	kHz	99.4	99.4
Damping time	ms	23	23
Feedback damping time	ms	$\sim$1	$\sim$1

- Beam-beam modes $Q_{x,1} = 0.509, \quad Q_{x,2} = 0.564$
- Horizontal tunes are closed to the half integer

$$Q_{x,2} \neq Q_{x,1} + \xi$$

FFT analysis of the dipole oscillation excited harmonically

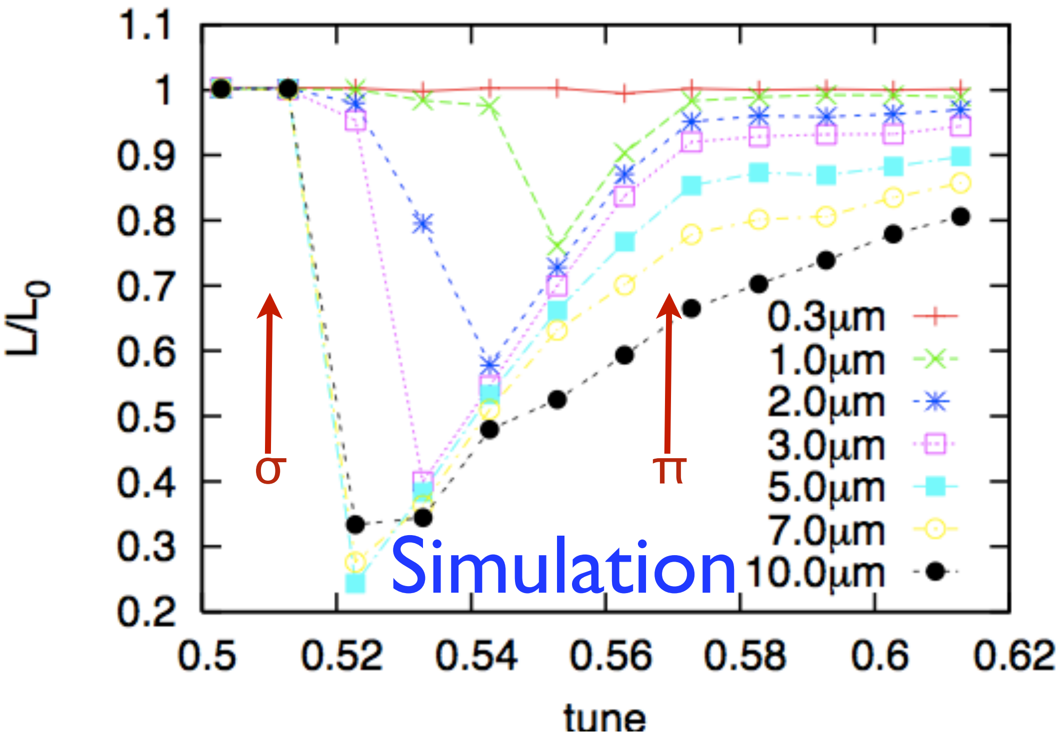


Peaks appear at the excitation frequencies

FFT spectra with 1μm excitation.

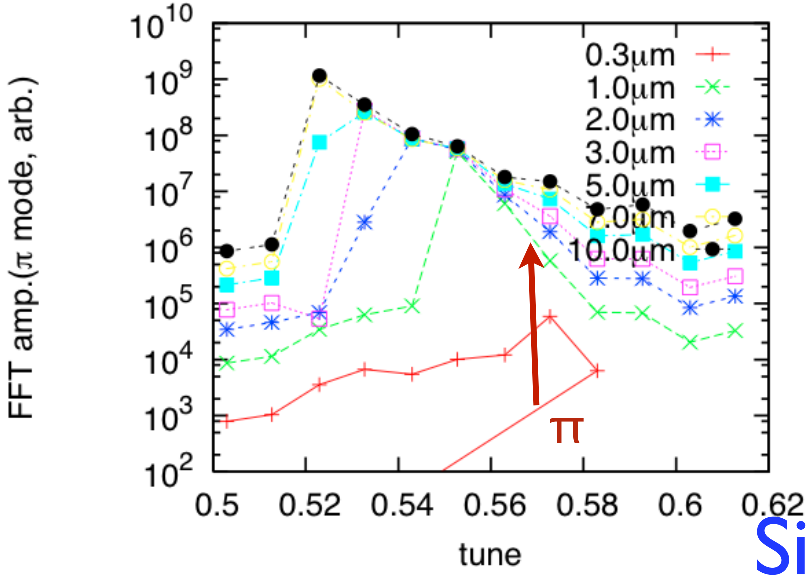
- Harmonic excitation of beam ν_{cc}=0.51-0.61
- FFT and response for excitation
- bunch-by bunch feedback (100 turn).

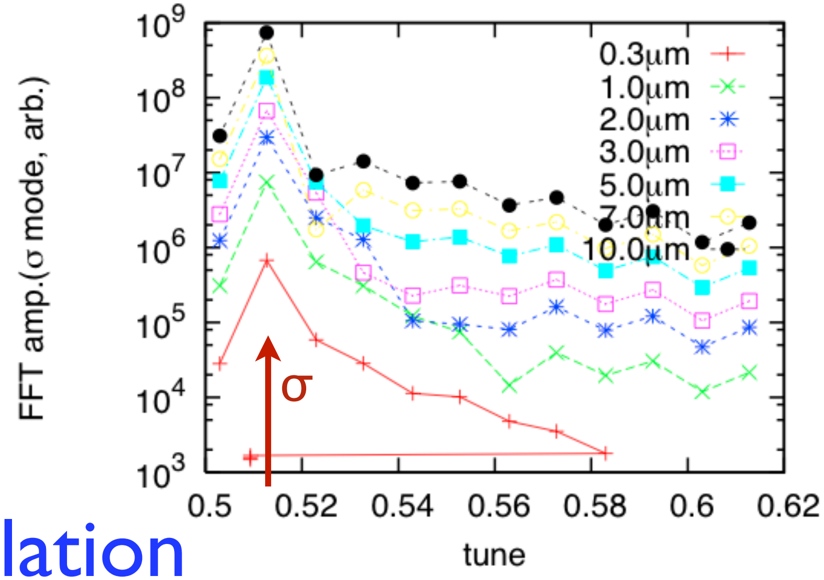
Luminosity response for the harmonic excitation



- Jump phenomenon is seen like Duffing system.
- A large amplitude excitation causes strong luminosity degradation near σ mode tune. A small excitation causes small degradation slightly below π mode tune.

FFT amplitude of π and σ mode oscillation

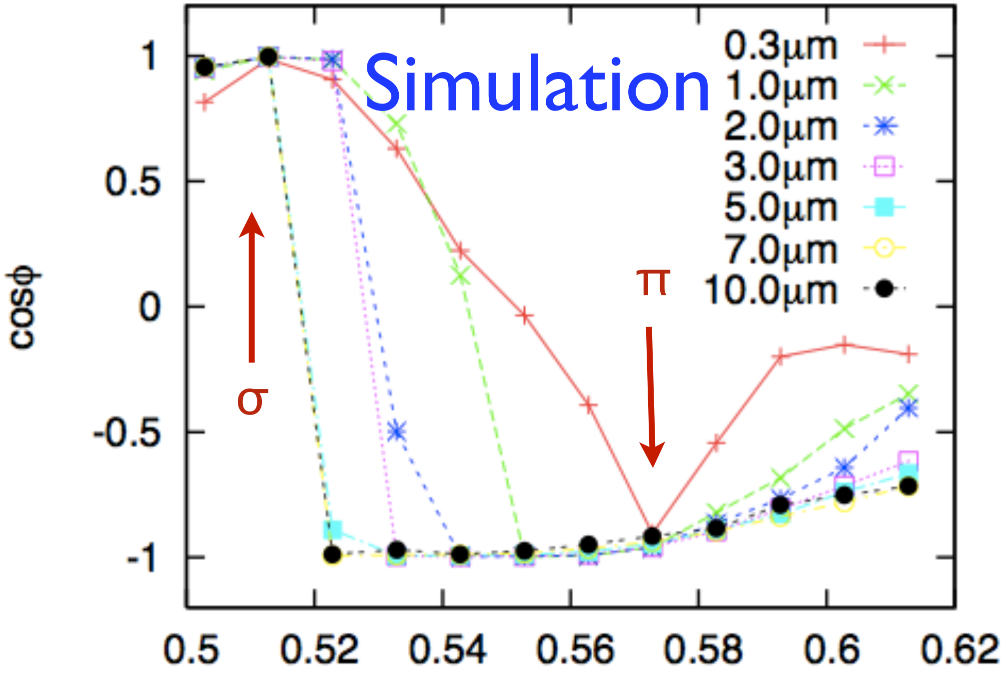




Simulation

- FFT of $x_e - x_p(\pi)$ and $x_e + x_p(\sigma)$.
- π mode behaves the same feature as that of the luminosity.
- σ mode oscillation appear but does not degrade the luminosity.

Phase jumping between π and σ mode



- The weak and strong luminosity degradations are caused by π mode oscillation.

Luminosity life time evaluation for LHC and HL-LHC

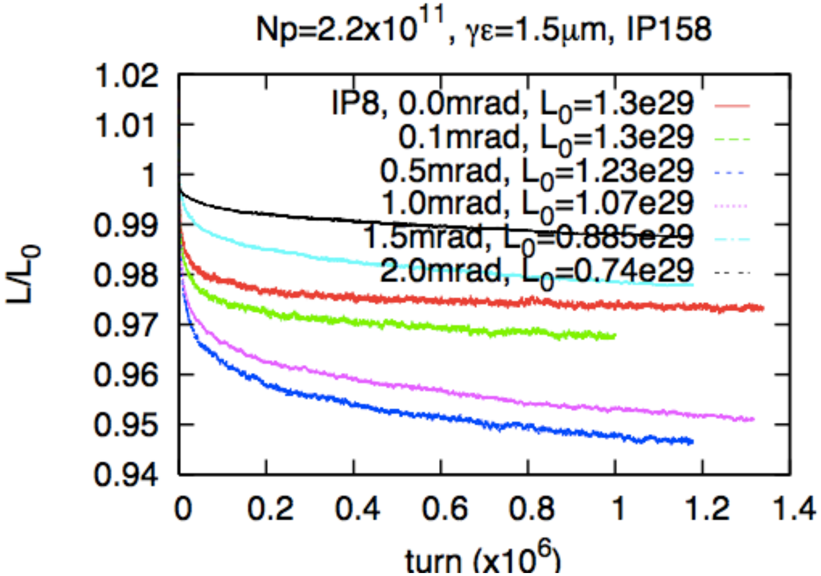
- Use weak-strong simulation. Such slow luminosity decrement is difficult to be evaluated by 3D strong-strong, because of too heavy and unavoidable numerical noise.

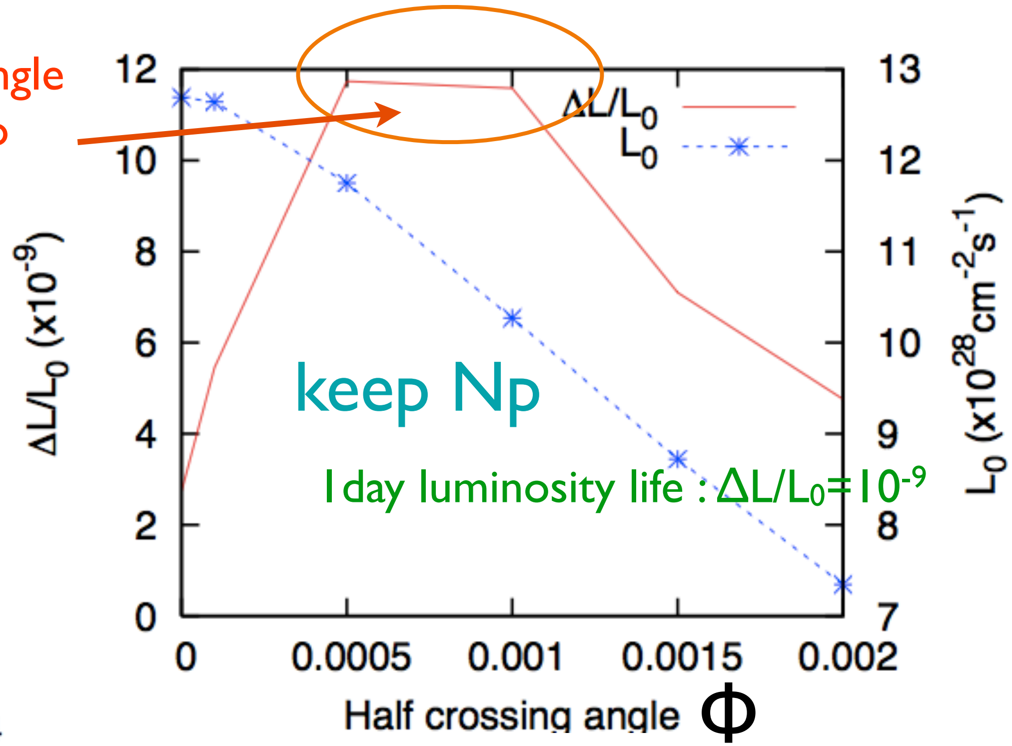
- Is effect of crossing angle seen in LHC 3.5TeV?
- Possible parameter search for HL-LHC.

Crossing angle effect in LHC

- Simulation of luminosity degradation due to crossing angle in the present operation.
- E=3.5TeV, Np= 2.2×10^{11}, σ_z=0.12m, β^*=10m $\gamma\varepsilon=1.5\times10^{-6}$
- IP8 Φ(half)=2mrad, IP1&5 Φ(half)=0mrad

Depending on the choice of crossing angle at IP8, luminosity degradation due to crossing angle may be visible.

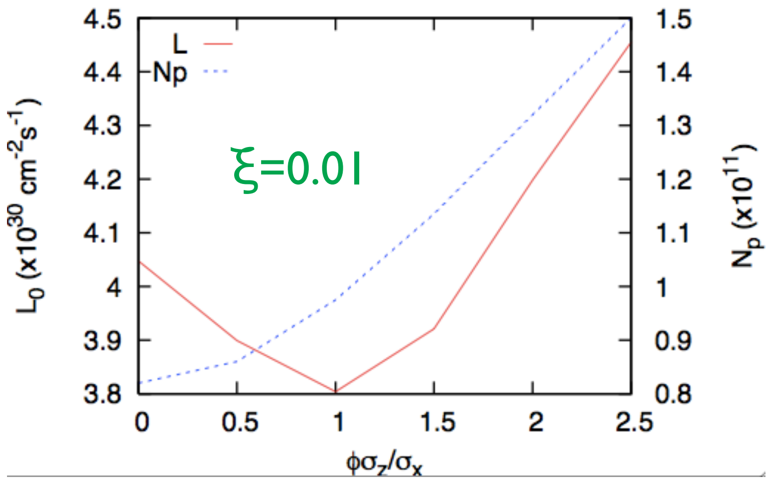


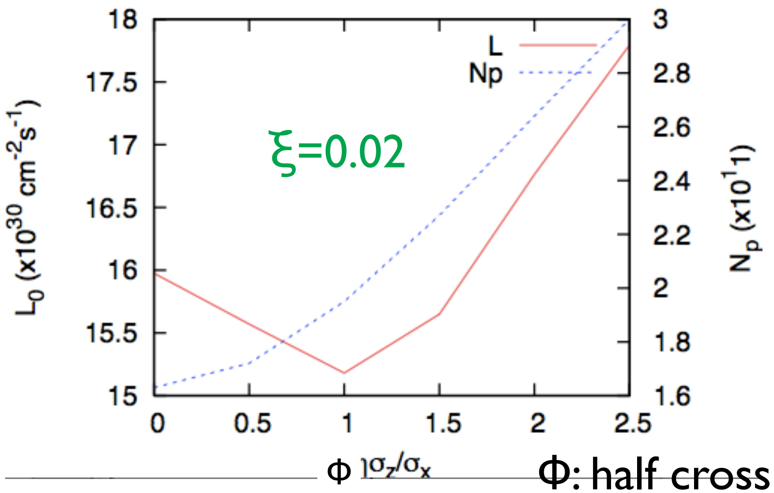


Possible Parameters for HL-LHC

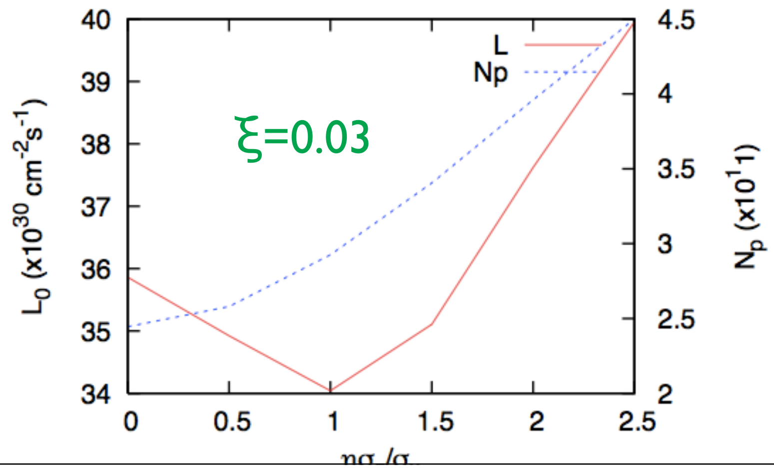
proposed by F. Zimmermann

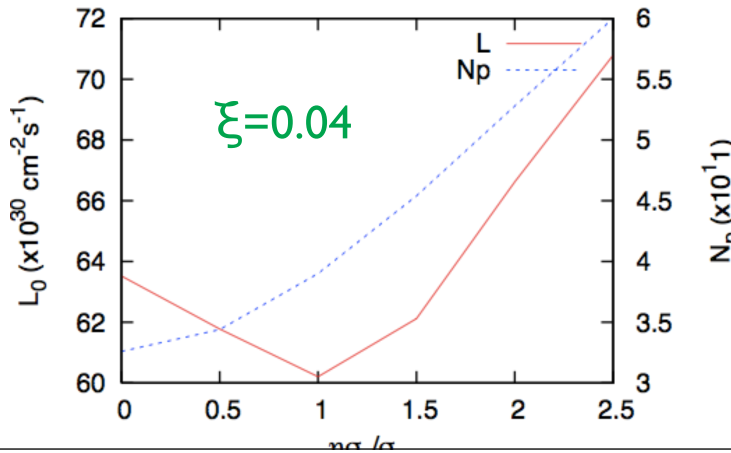
- E=7TeV, γε=2μm, β*=0.55m, Collision at IP1& 5
- Total Beam-beam parameter 0.01, 0.02, 0.03, 0.04.
- Crossing angle Φσz/σx=0, 0.5, 1.0, 1.5, 2.0, 2.5





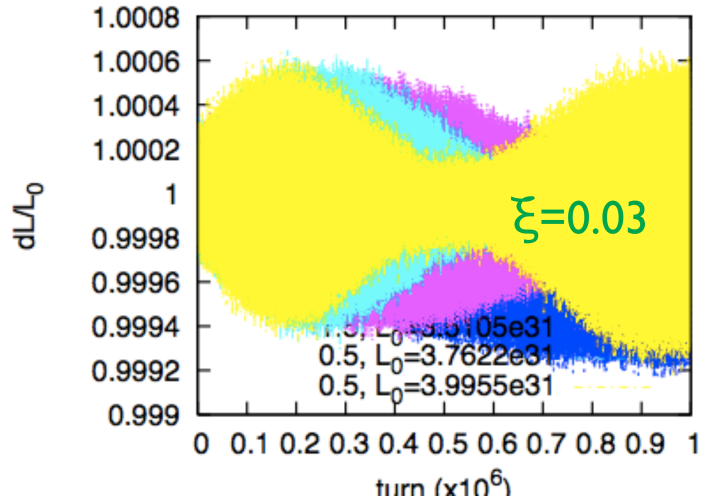
Φ: half crossing angle

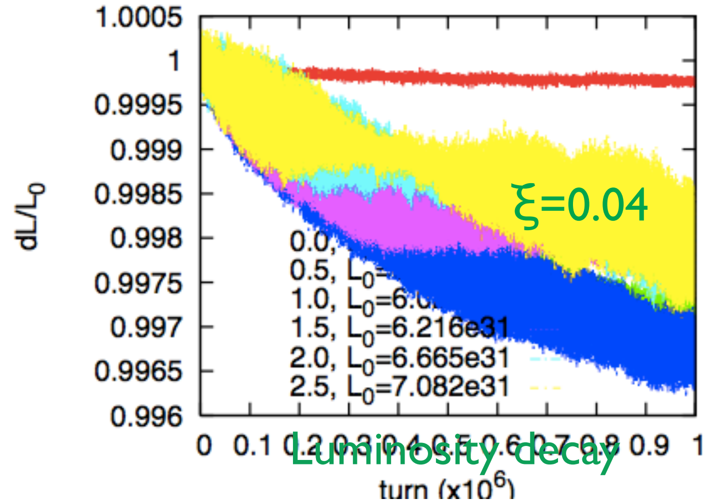


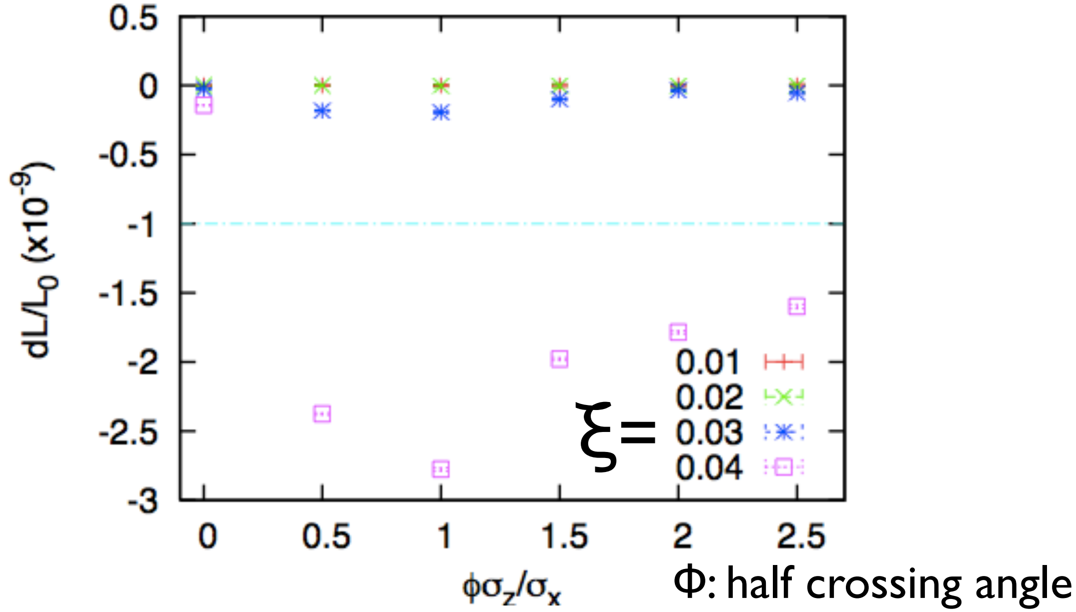


Crossing angle effect in HL-LHC

- Strategy for choice of the beam-beam parameter, bunch length and crossing angle in HL-LHC





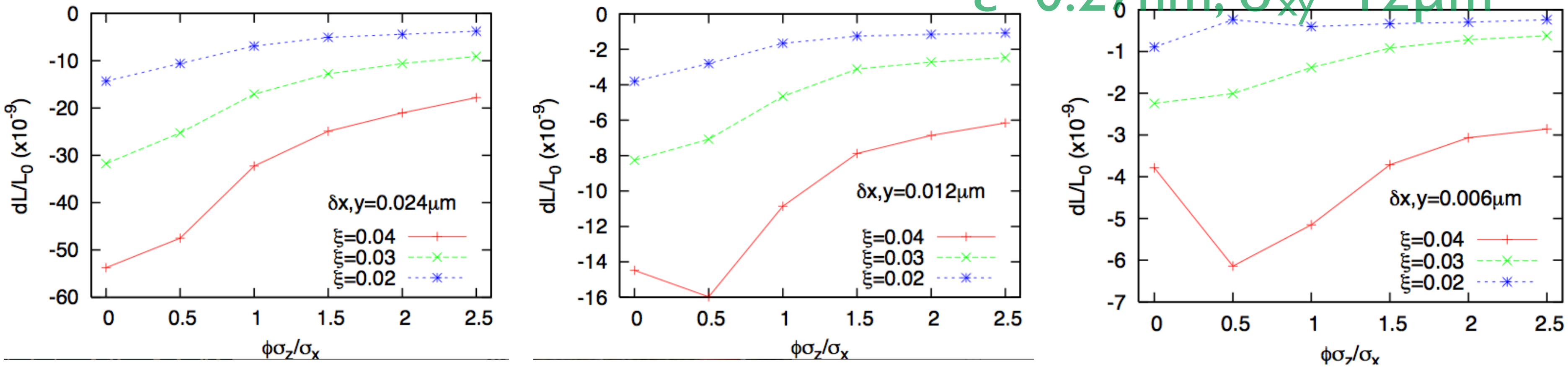


Luminosity depending on crossing angle is remarkable at ξ=0.04.

Effect of beam noise

- Turn-by-turn fluctuation of collision offset degrades luminosity performance.

ε=0.27nm, σ_{xy}=12μm



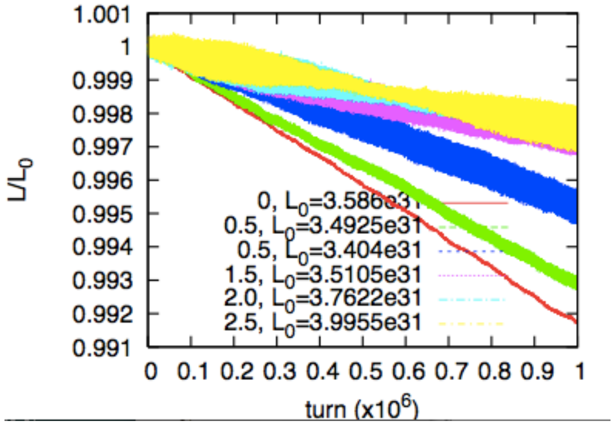
- Noise level should be <0.05%σ_{xy}.

$dL/L_0=10^{-9}$: 1day

- Head on (zero crossing angle) is sensitive for the noise.

Incoherent growth of 1day irrelevant to beam-beam

$$\delta x_{incoh}/\sigma_x = \sqrt{10^{-9}} = 0.003\% \ll \delta x$$



ξ=0.03
0.1% noise

phase jitter tolerance

$$\delta\psi_{RF} = \frac{\omega_{RF}\delta x}{c\tan\phi}$$

Φ: half crossing angle

Summary

- The experiments on crab cavity noise done in KEKB is well explained by the strong-strong simulations. Feasibility of the simulation was checked.
- Luminosity degradation due to crossing angle may be observable in LHC 3.5TeV.
- Choices of the beam-beam parameter, crossing angle, and turn-by-turn collision offset noise for HL-LHC, next page, for example.

Possible parameter choices from the results ($\gamma\varepsilon$=2μm, β^*=0.55m)

- ξ=0.03, N_p=2.5x10^{11}, $\Phi\sigma_z/\sigma_x$=0, N_b=2800, L=10^{35} cm^{-2}s^{-1}, Noise ~0.03%σ.
- ξ=0.03, N_p=4x10^{11}, $\Phi\sigma_z/\sigma_x$=2, N_b=1400, L=0.5x10^{35} cm^{-2}s^{-1}, Noise ~0.06%σ.
- ξ=0.02+α, N_p=2.5x10^{11}, $\Phi\sigma_z/\sigma_x$=1, N_b=2800, L=0.5x10^{35} cm^{-2}s^{-1}, Noise ~0.05%σ.
- .....

Private opinion