Luminosity boost by head-on (crab) collision

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Introduction

- Target luminosity

  $L_{tot} = 10^{35} \sim 10^{36}\ cm^{-2}s^{-1}$

- f_{RF}=500MHz E_L=3.5GeV E_H=8GeV
- $L_b = 2x10^{31} \sim 2x10^{32}\ cm^{-2}s^{-1}$
- $N_L \xi/\beta_y = 1.6x10^{12} \sim 1.6x10^{13}\ m^{-1}$
- $N_H = 3.5\ N_L/8$

$$L_{tot} = \frac{N\gamma\xi_y}{2r_e\beta_y} f_{rep}$$

How do we choose these parameters?

- $L = 10^{35}\ cm^{-2}s^{-1}$, $N_L\xi/\beta_y = 1.6x10^{12}$
  $\beta_y = 3mm$, $\xi_y = 0.05$,
  $N_L = 9.6x10^{10}$, $I_L = 8\ A$
  Crossing angle =15 mrad

- $L = 10^{36}\ cm^{-2}s^{-1}$, $N_L\xi/\beta_y = 1.6x10^{13}$
  $\beta_y = 3mm$, $\xi_y = 0.2$,
  $N_L = 2.4x10^{11}$, $I_L = 19\ A$
  without drastic change of Magnet and RF.

Super KEKB

WWW page

Machine Parameters of the SuperKEKB

	LER	HER	
Horizontal Emittance	33	33	nm
Vertical Emittance	2.1	2.1	nm
x-y coupling	6.4	6.4	%
Beam current	9.4	4.1	A
Number of bunches	5018 (2% abort gap)		
Bunch current	1.87	0.817	mA
Bunch spacing	0.6		m
Half crossing angle	15		mrad
Luminosity reduction R_L	0.748		
ξ_x reduction $R_{\xi x}$	0.691		
ξ_y reduction $R_{\xi y}$	0.916		
Bunch length	3	3	mm
Radiation loss U_0	1.23	3.48	MeV/turn
Betatron tune ν_x / ν_y	45.515/43.57 ?	44.515/41.57 ?	
beta's at IP β_x^* / β_y^*	15/0.3	15/0.3	cm
beam-beam parameters ξ_x / ξ_y	0.068/0.05	0.068/0.05	
Beam lifetime	~150	~150	min.
Luminosity	1.0		10^{35}/cm^2/sec

Do we get the luminosity?

- Collision scheme

  Flat beam with/without crossing angle

  Long bunch

  Round beam

  Four-beam

  ....
- Computer simulations of beam-beam interactions inform the feasibility for the high luminosity.

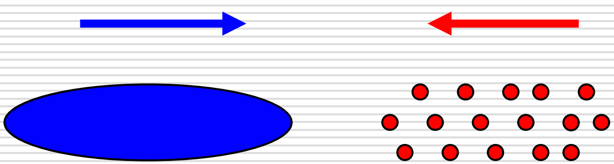
Beam-beam simulation methods

- Weak-strong model

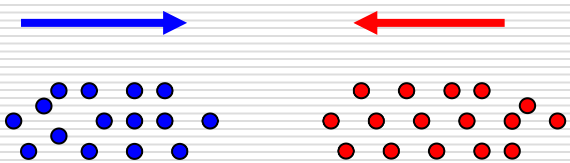
  One beam is represented by macro-particles, while another beam is represented by fixed Gaussian charge distribution.

- Strong-strong model

  Both beams are represented by macro-particles.



Weak strong



Strong-strong

Crossing angle and crab crossing

- Transformation from Lab. frame to head-on frame.

(ϕ: half crossing angle)

$$x^* = \tan\phi\, z + [1 + h_x^* \sin\phi]\, x$$

$$p_x^* = (p_x - h\tan\phi)/\cos\phi$$

$$y^* = y + h_x^* \sin\phi\, x$$

$$p_y^* = p_y^* / \cos\phi$$

$$z^* = z/\cos\phi + h_z^* \sin\phi\, x$$

$$p_z^* = p_z - p_x \tan\phi + h\tan^2\phi$$

$$h = p_z + 1 - \sqrt{(p_z+1)^2 - p_x^2 - p_y^2}$$

Linear part

$$\begin{pmatrix} 1 & 0 & 0 & 0 & \tan\phi & 0 \\ 0 & 1/\cos\phi & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/\cos\phi & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/\cos\phi & 0 \\ 0 & \tan\phi & 0 & 0 & 0 & 1 \end{pmatrix}$$

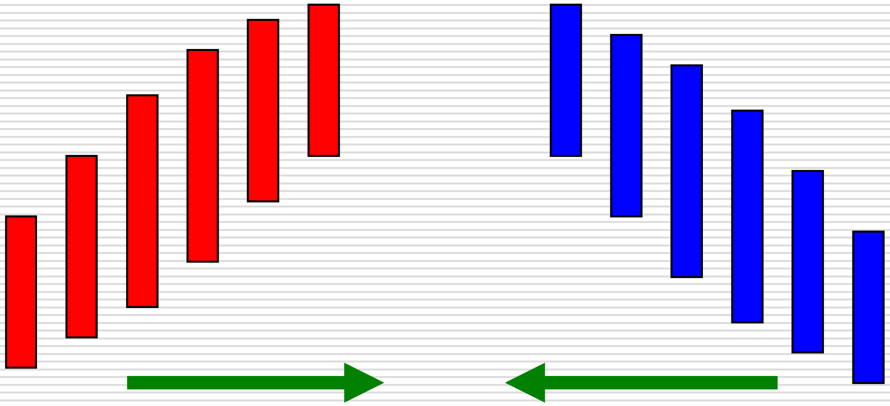
Crab cavity

- Crab cavity makes z dependent dispersion $\zeta_x = -\phi$ at IP, which cancels the crossing angle effect.

$$\begin{pmatrix} 1 & 0 & 0 & 0 & \zeta_x & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & \zeta_x & 0 & 0 & 0 & 1 \end{pmatrix}$$

Longitudinal slicing

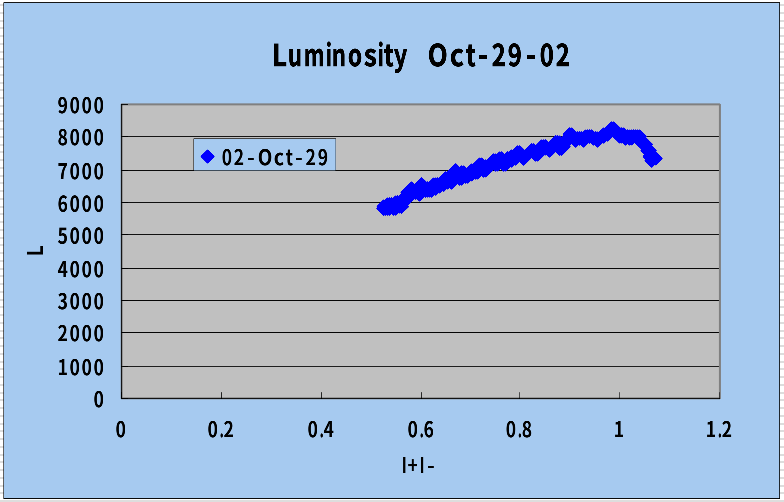
- A bunch is divided into some slices which include many macro-particles.
- Collision is calculated slice by slice.

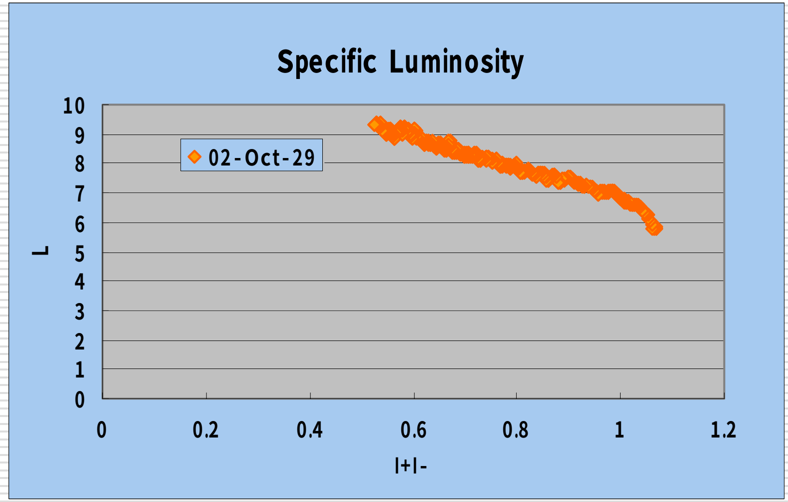


Achieved beam-beam parameter

- Finite crossing angle scheme quite succeeded in the present KEKB.
- Achieved beam-beam parameter was not remarkably large, 0.04～0.05, though it is just our design value.
- The world record is ～0.07 at CESR and is ～0.1 at LEP.

Present KEKB Oct. 29, 2002

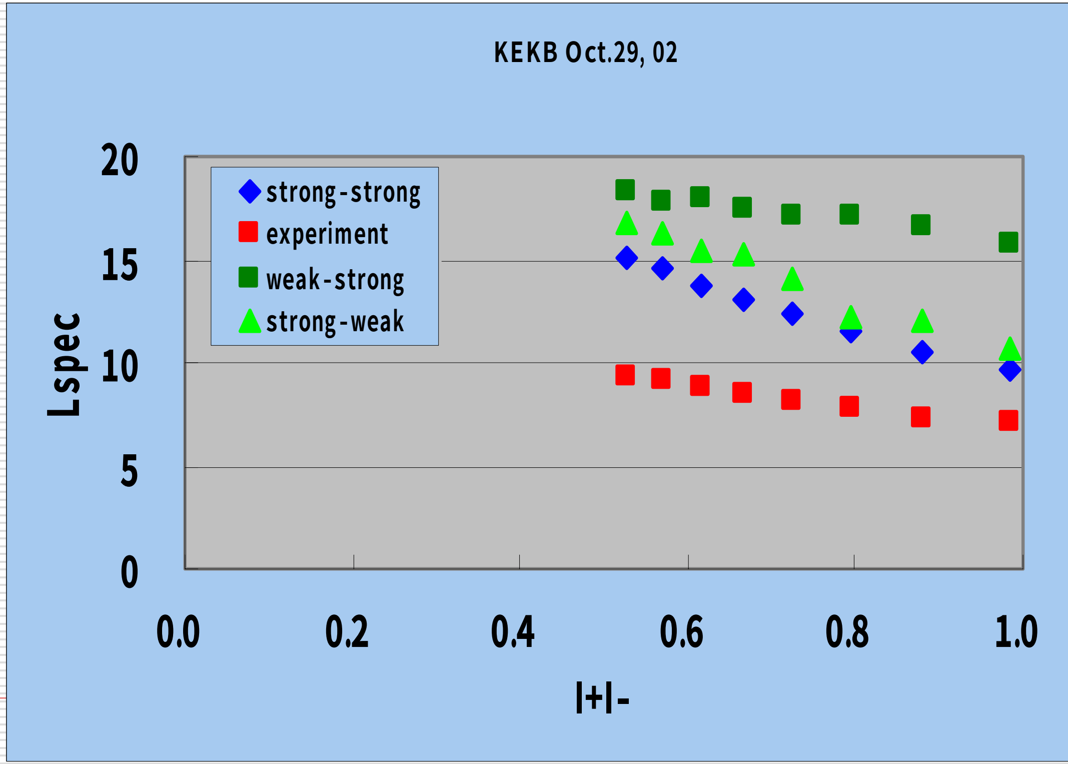




- L_{peak}=8.26x10^{33} cm^{-2}s^{-1} N_b=1184
- N_+= 7.7x10^{10} N_-=5.0x10^{10}
- $\varepsilon_{+,x}$ =18 nm $\varepsilon_{-,x}$ = 24 nm
- β = 7mm
- ν = 0.51/0.56

Simulation results for the present KEKB (Oct. 29, 02)

- Lspec obtained by simulation and experiment.



Experiment and simulation

- Luminosity by simulation is somewhat higher than experimental value.
- Experimental luminosity may be larger for longer bunch spacing. In a measurement, it was 20% larger.
- The agreement becomes better due to a detailed choice of parameters (Tawada).

- Weak-strong and strong-strong simulations coincide each other.

Study for effects of crossing angle

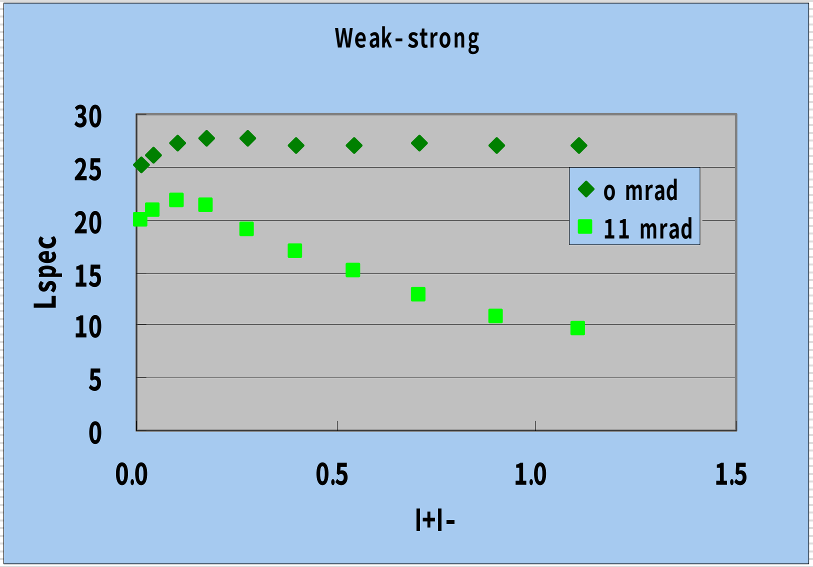
Model lattice parameters

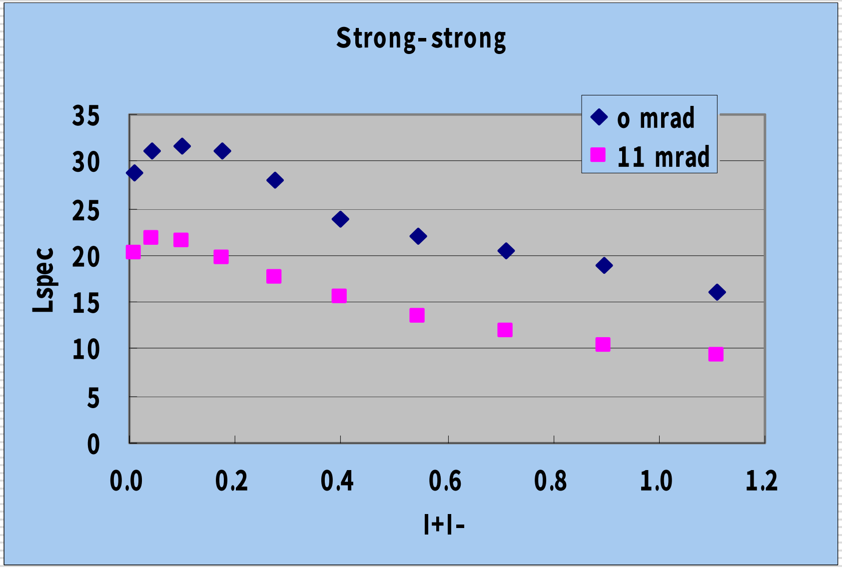
- To avoid flip-flop phenomenon, N/γ is kept equal for the both rings.
- ε_x = 18mrad $\varepsilon_y = 0.01\ \varepsilon_x$
- β_x = 60cm β_y = 7mm
- $N_+ = 8/3.5\ N_-$
- σ_z = 7mm

Specific luminosity for various current product ($I_+ I_-$).

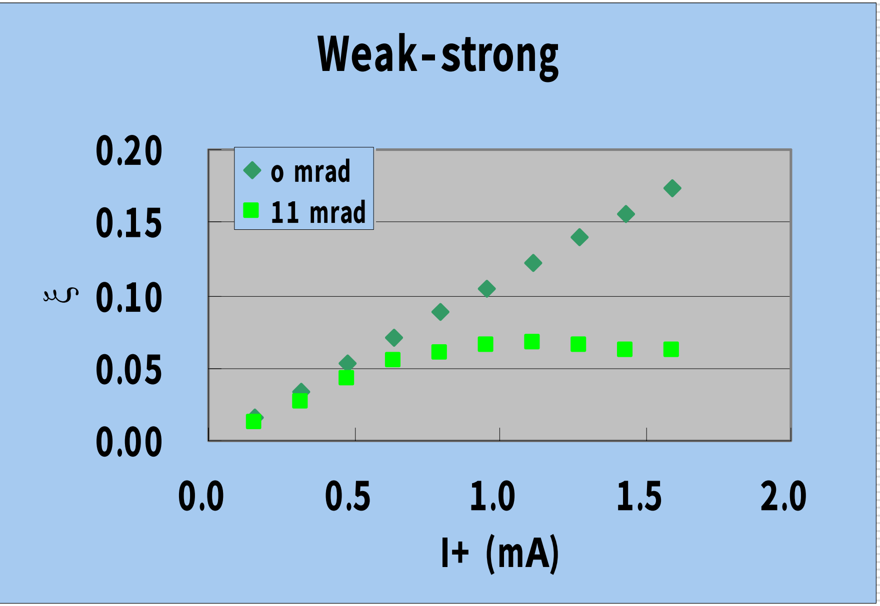
- ϕ = 0mrad and 11mrad

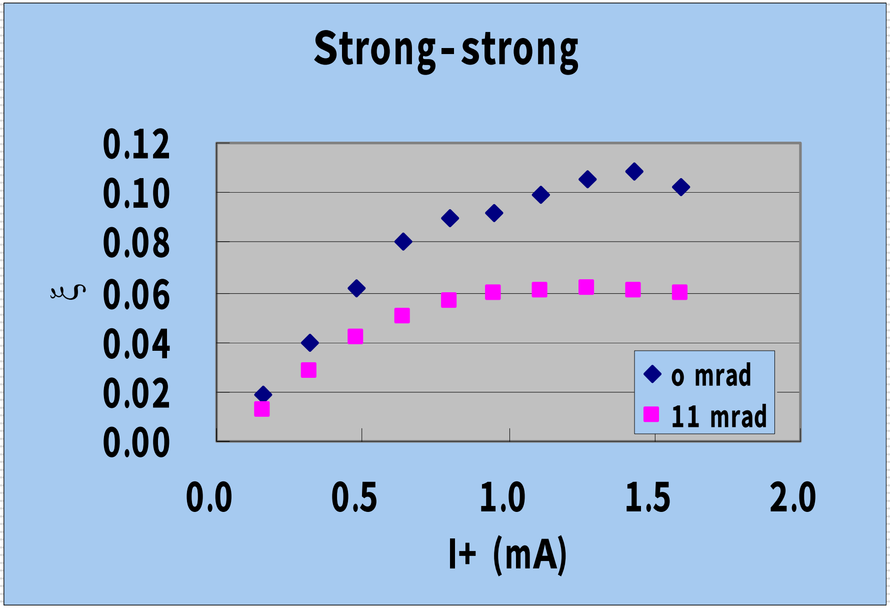
Weak strong strong-strong





Beam-beam parameter





Effect of crossing angle

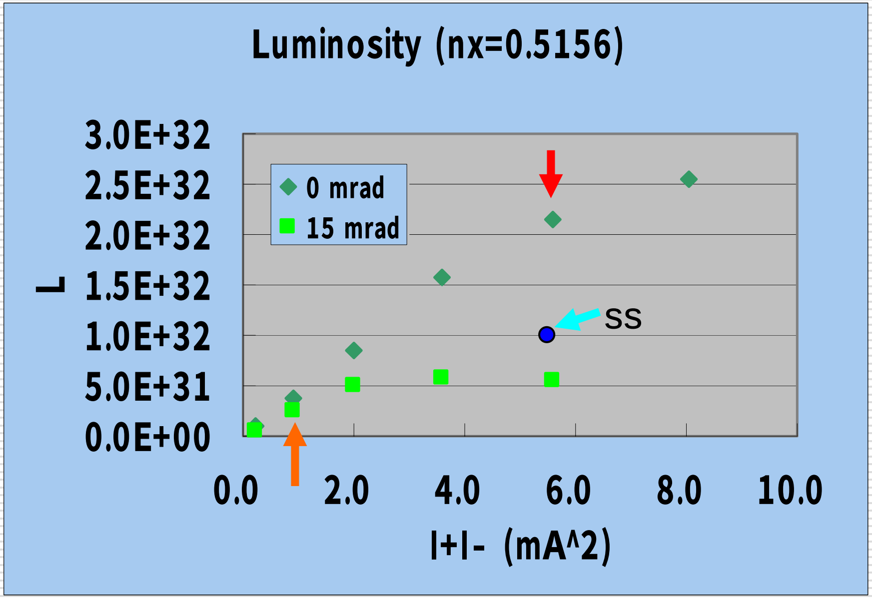
- The weak-strong and strong-strong show similar results for $\phi = 11$ mrad.
- No beam-beam limit for $\phi = 0$ mrad in the weak-strong.
- There is a beam-beam limit for $\phi = 0$ mrad in the strong-strong simulation.
- Crossing angle degrades luminosity in either case.

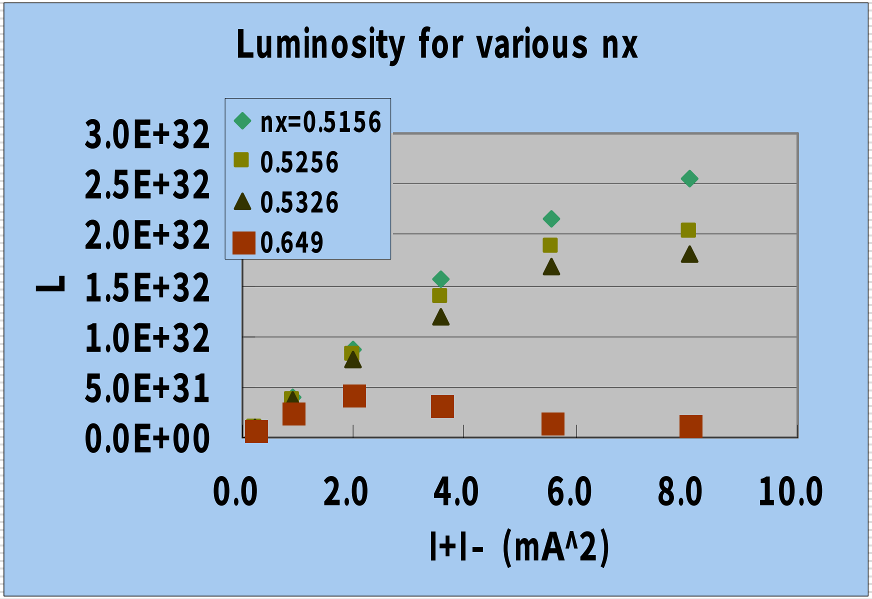
- Crab cavity upgrades luminosity.

Super KEKB

- Target: L_b = $2x10^{31}$ ~ $2x10^{32}$ $cm^{-2}s^{-1}$
- Super KEKB: L_b = $2x10^{31}$ $cm^{-2}s^{-1}$, crossing angle 15 mrad.
- Hyper KEKB: L_b = $2x10^{32}$ $cm^{-2}s^{-1}$, head-on collision and higher current.

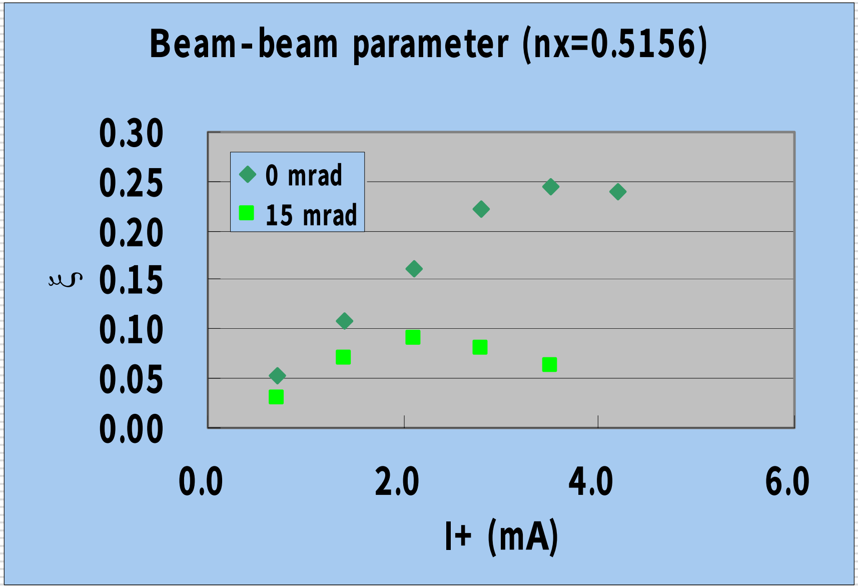
Simulation for Super KEKB parameter (weak-strong)

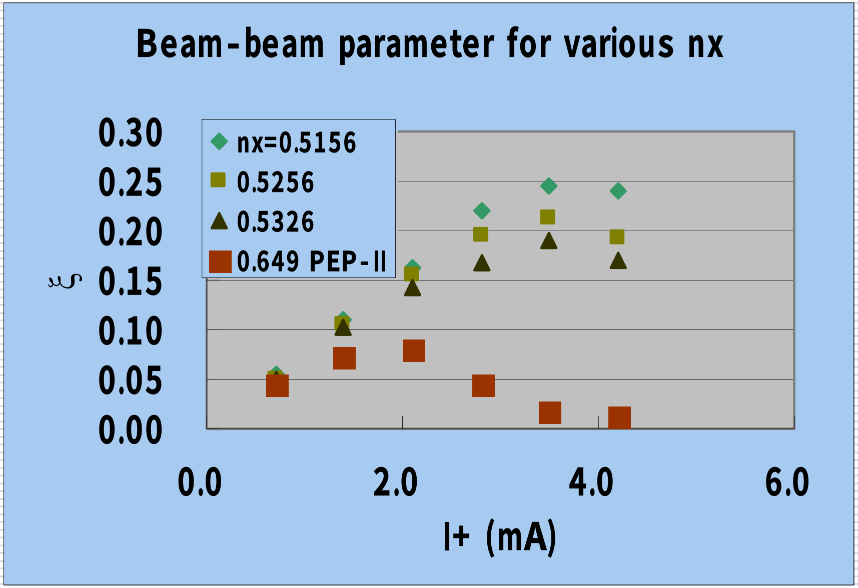




- The luminosity $L_b = 2\times10^{31}$ cm^{-2}s^{-1} was achieved for the crossing angle 15mrad.
- The luminosity $L_b = 2\times10^{32}$ cm^{-2}s^{-1} was achieved at $N_L=2.2\times10^{11}$ $N_H=10^{11}$.
- Luminosity behavior depends on tune.

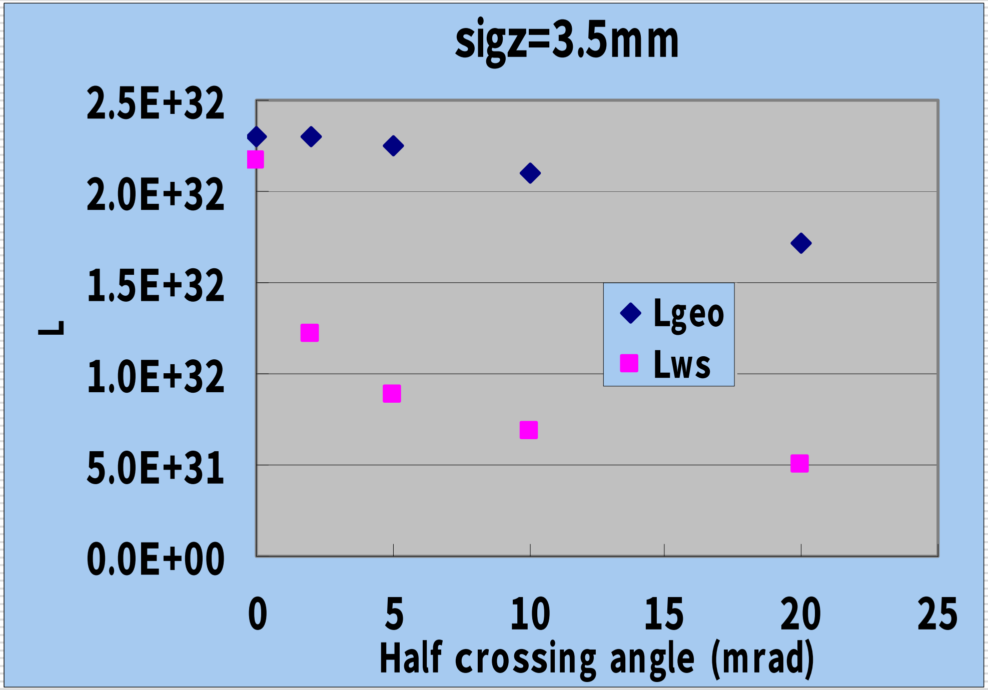
Beam-beam parameter obtained by the weak-strong simulation





- ξ is limited about 0.25 for the head-on collision, while is limited 0.09 for the crossing angle 15mrad.
- ξ behavior depends on tune.

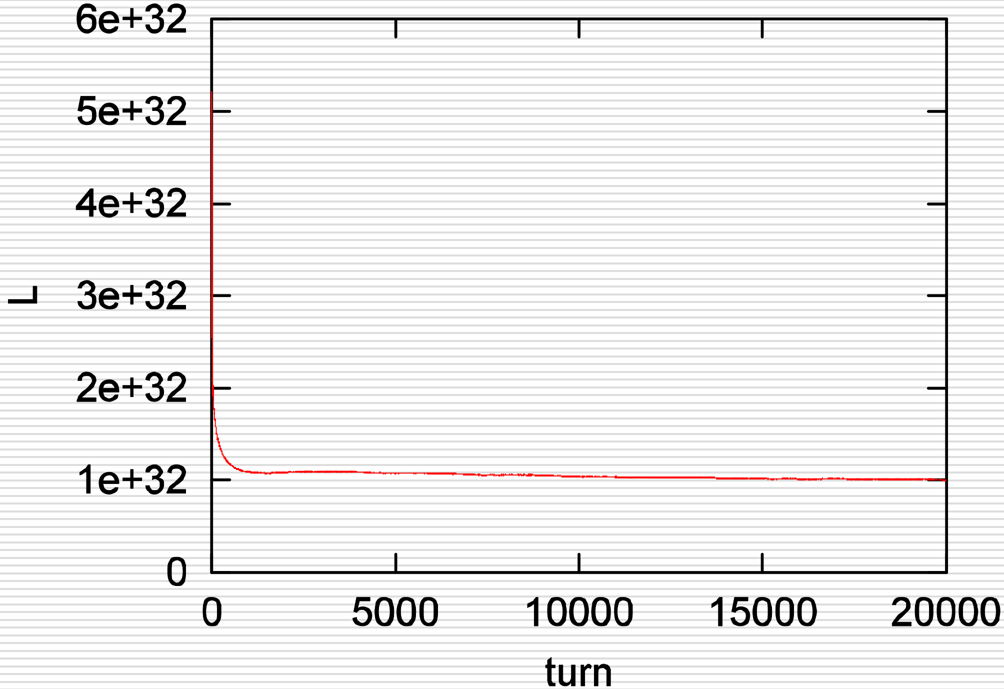
Crossing angle dependence



- Luminosity at $\phi = 0$ mrad is very high.
- Narrow peak near $\phi = 0$ mrad.
- This behavior is remarkable for large ξ.

Strong-strong simulation

Is $L_b = 2\text{x}10^{32}$ $cm^{-2}s^{-1}$ obtained even by the strong strong simulation?



- $L_b = 8\sim9\text{x}10^{31}$ $cm^{-2}s^{-1} < 2\text{x}10^{32}$ $cm^{-2}s^{-1}$.
- A beam-beam limit is seen in the strong-strong.
- $L_{tot} = 4\text{x}10^{35}$ $cm^{-2}s^{-1}$ can be expected.

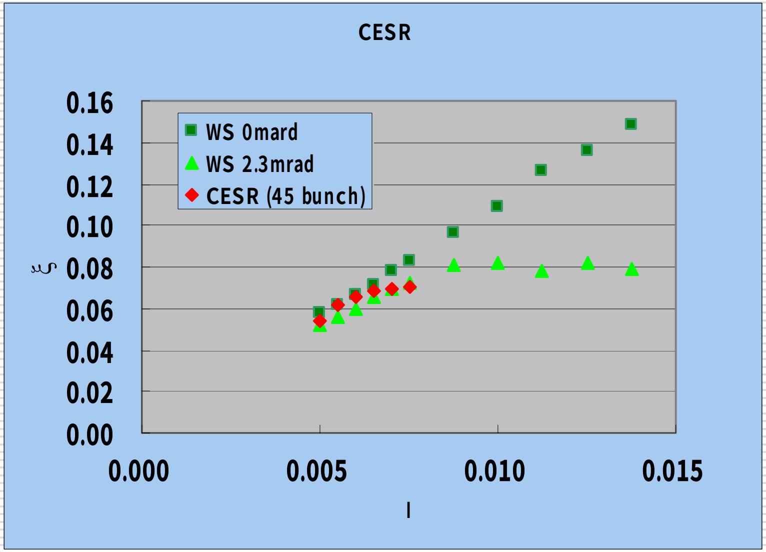
Candidate of Hyper KEKB parameter

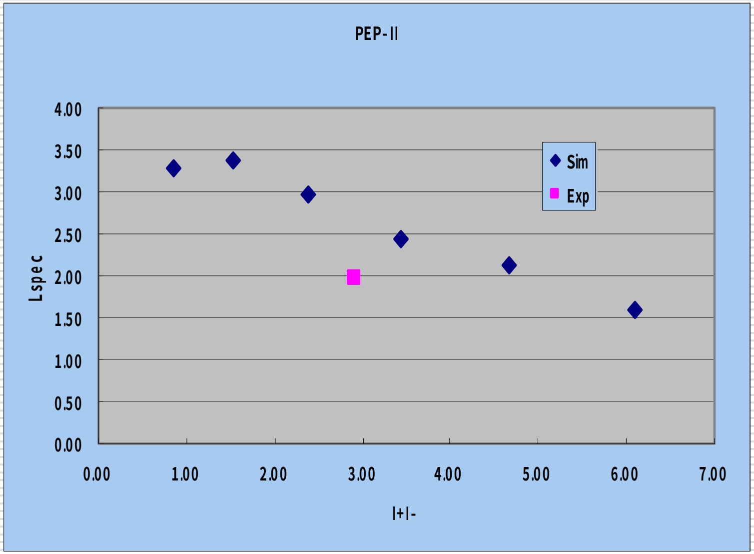
- Low beta and head-on collision make possible a higher ξ. It means that the luminosity is achieved by lower total current.
- β_x = 15 cm, β_y = 3 mm, σ_z = 3.5 mm, ϕ =0 mrad, ε_x = 33 nm, ε_y = 0.33nm, $N_L=2.2\times10^{11}$ $N_H=10^{11}$
- L_b = 2×10^{32} $cm^{-2}s^{-1}$, L_{tot} = 1×10^{36} $cm^{-2}s^{-1}$, ξ = 0.2 by the weak-strong.
- L_b = $8\sim9\times10^{31}$ $cm^{-2}s^{-1}$, L_{tot} = 4×10^{35} $cm^{-2}s^{-1}$ ξ = 0.09~0.1 by the strong-strong.

Which is reliable w.s. or s.s.?

- Is w.s. model reliable to estimate the beam-beam limit?
- Unphysical numerical noises (PIC algorithm or longitudinal slicing) may degrade in the s.s. simulation in such a high current.
- We need more studies why the beam-beam limit observed in the s.s. simulation.
- We do not discard the result of weak-strong now.

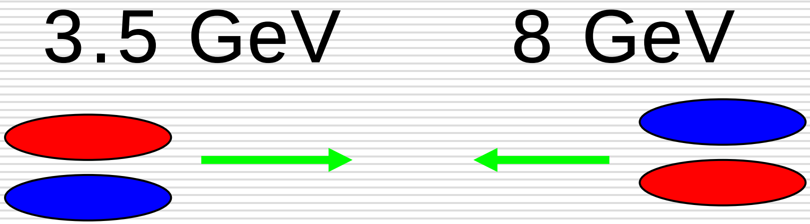
Results for other machines obtained by w.s..





Four beam (with Ohnishi)

- Collision of neutralized beams containing both of e+ and e- charge.



Eigenmode of dipole motion

- $\nu = \nu_0 + \xi$ $\quad \vec{\phi}_\beta(e^\pm) - \overleftarrow{\phi}_\beta(e^\mp) = \pi$

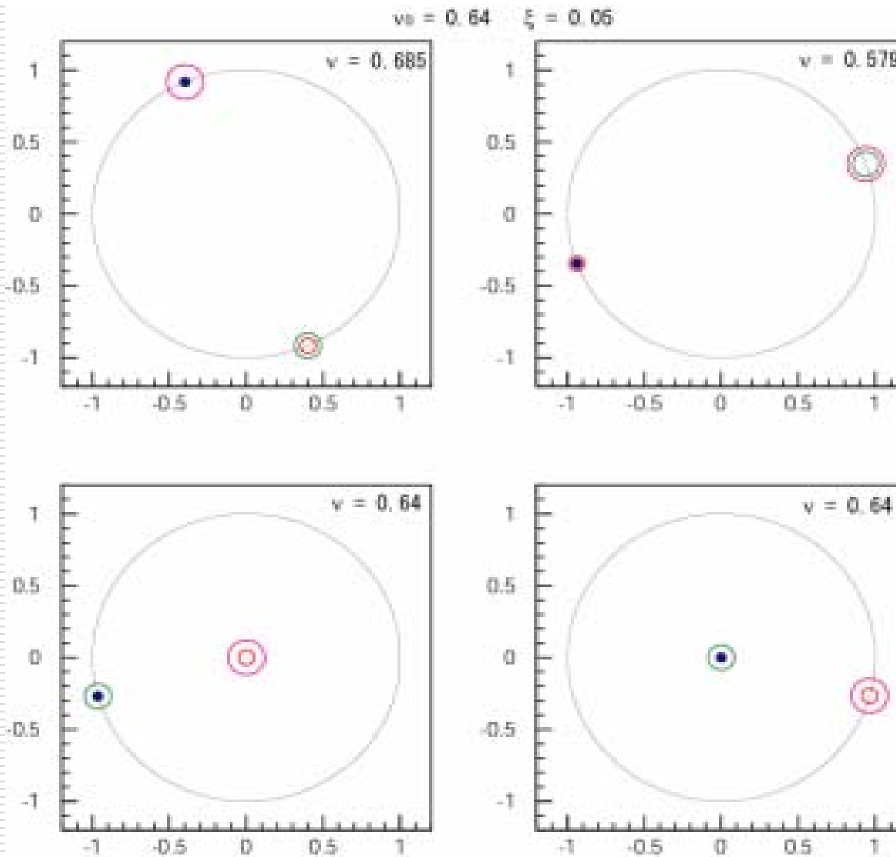
  $\vec{\phi}_\beta(e^\pm) - \overleftarrow{\phi}_\beta(e^\pm) = 0$

- $\nu = \nu_0 - \xi$ $\quad \vec{\phi}_\beta(e^\pm) - \overleftarrow{\phi}_\beta(e^\mp) = 0$

  $\vec{\phi}_\beta(e^\pm) - \overleftarrow{\phi}_\beta(e^\pm) = \pi$

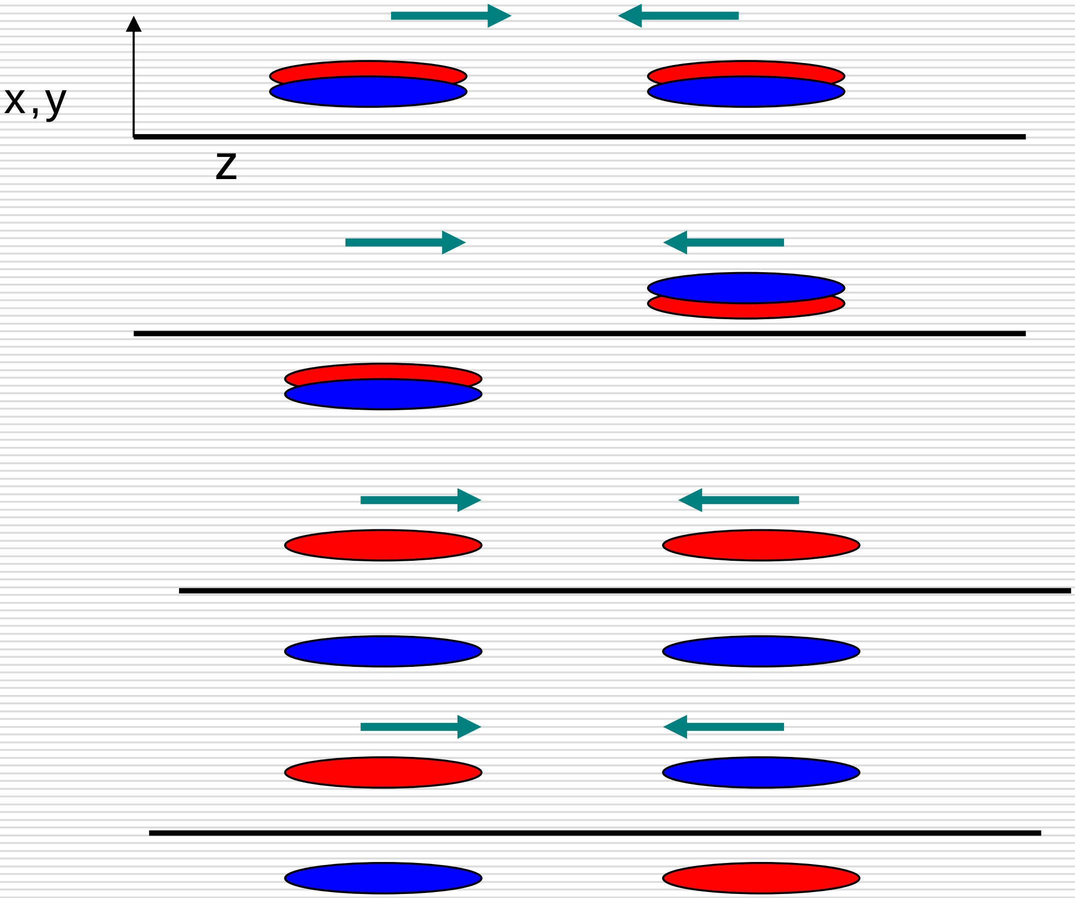
- $\nu = \nu_0$ $\quad \vec{\phi}_\beta(e^+) - \vec{\phi}_\beta(e^-) = 0$

  $\overleftarrow{\phi}_\beta(e^+) - \overleftarrow{\phi}_\beta(e^-) = 0$



Coherent tune shift similar as that of two-beam

4 eigenmodes of four-beam collision



No tune shift

$\nu = \nu_0$

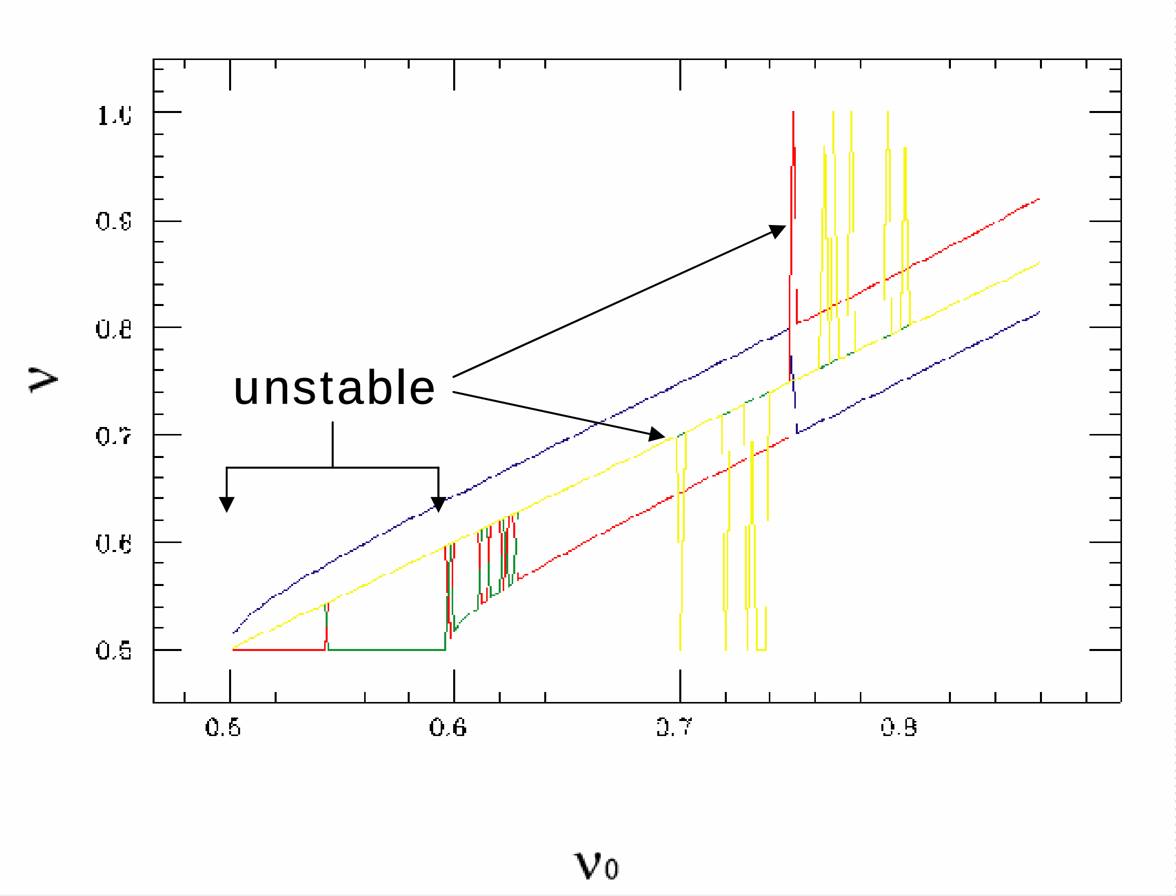
Focusing

$\nu = \nu_0 + \xi$

Defocusing

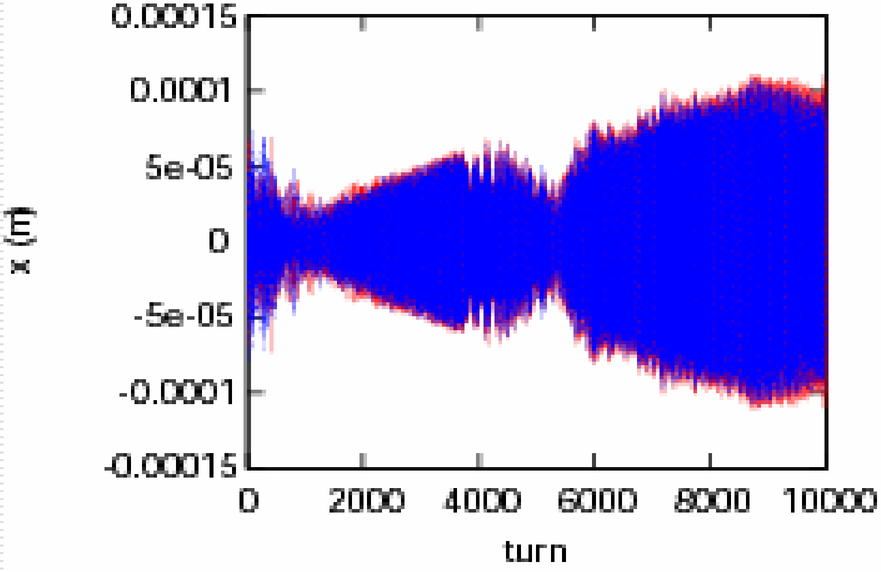
$\nu = \nu_0 - \xi$

Eigenvalue of each mode



Strong-strong simulation (2D)

- Hyper KEKB parameter
- Stable tune for the dipole mode.



- Strong coherent motion is seen.

Summary for four-beam scheme (preliminary)

- Incoherent effect is cancelled by the neutralization, but coherent effect remains.
- Twice more resonances.
- Weak Landau damping.
- Does feed-back help the coherent mode?

- We have not had a reliable solution for the four beam scheme yet.