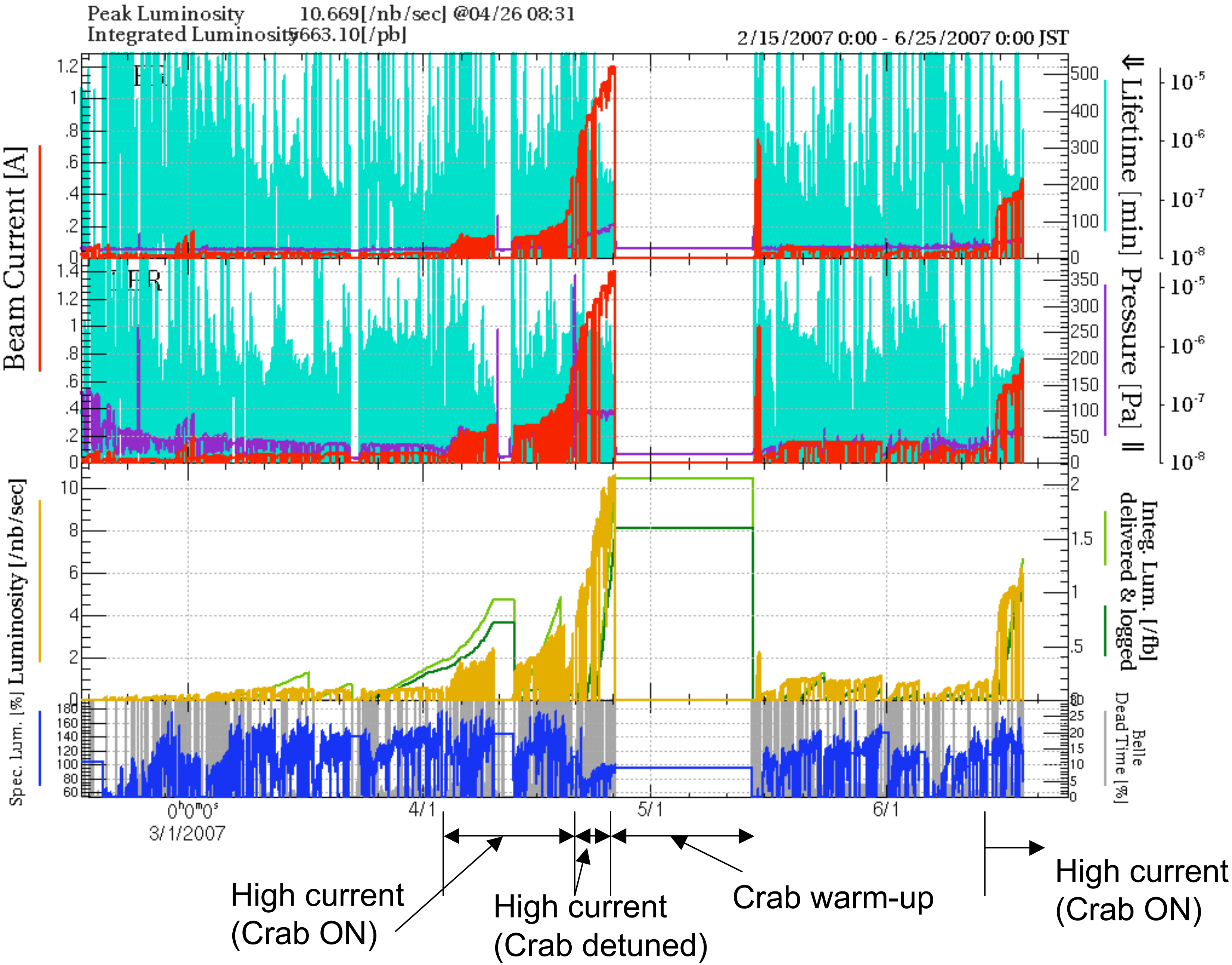
Commissioning progress before July

Y. Funakoshi
(KEK)

Beam Operation with crab cavities

- Dedicated machine study (Feb. 13 ~ June 30 2007)
  - Feb. 19 ~ Mar. 19 : reported by H. Koiso (last MAC)
  - Mar. 20 ~ June 30: This Talk
- Physics run with crab cavities (Oct. 2 ~ Dec. 17): To be reported by H. Koiso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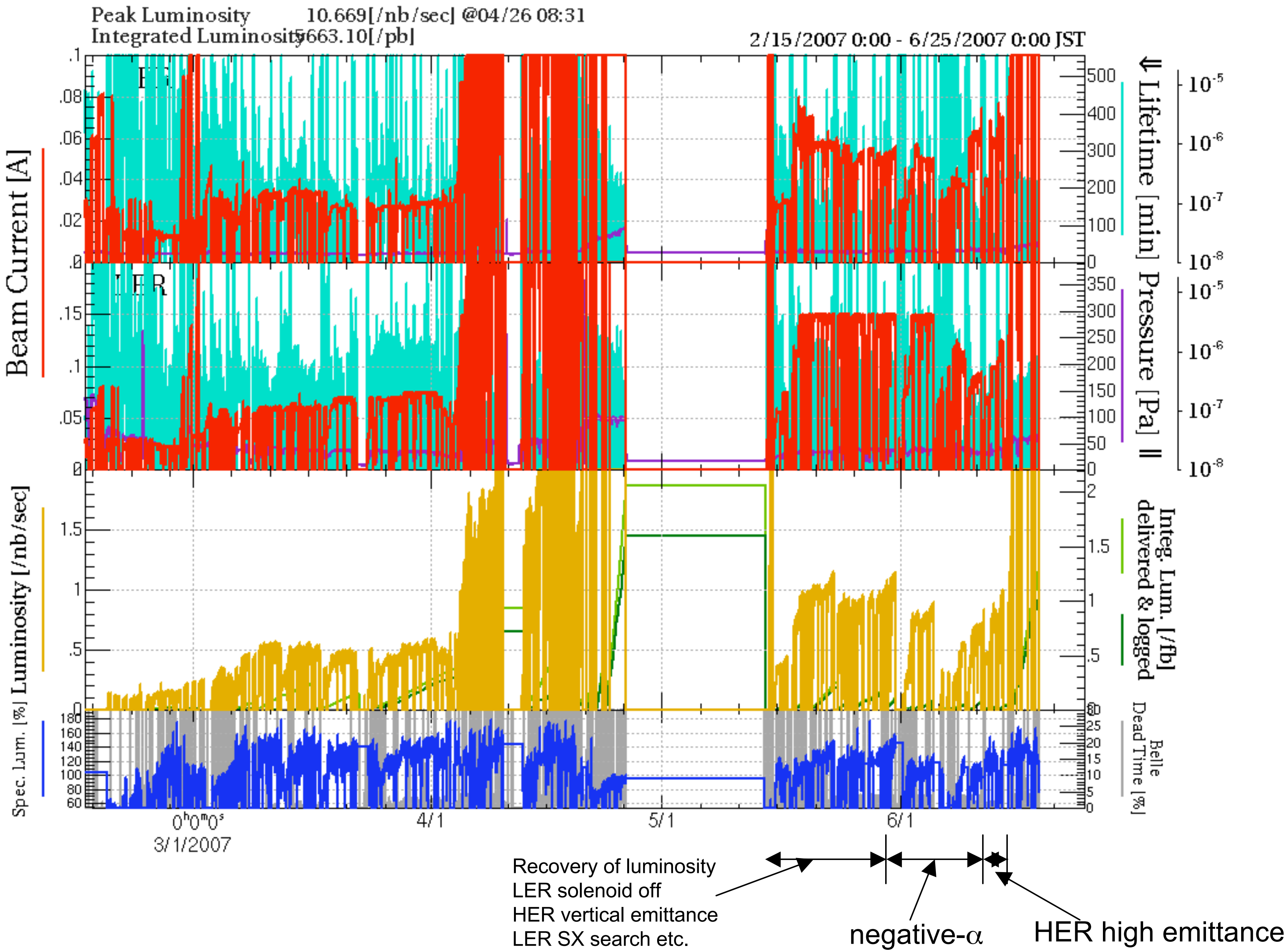
Integrated Luminosity 5663.10[/pb]
2/15/2007 0:00 - 6/25/2007 0:00 JST
Beam Current [A]
HER
LER
⇓ Lifetime [min]
Pressure [Pa] ⇓
Luminosity [/nb/sec]
Integ. Lum. [/fb] delivered & logged
Spec. Lum. [%]
Belle Dead Time [%]
0h0m0s
3/1/2007
4/1
5/1
6/1
High current (Crab ON)
High current (Crab detuned)
Crab warm-up
High current (Crab ON)



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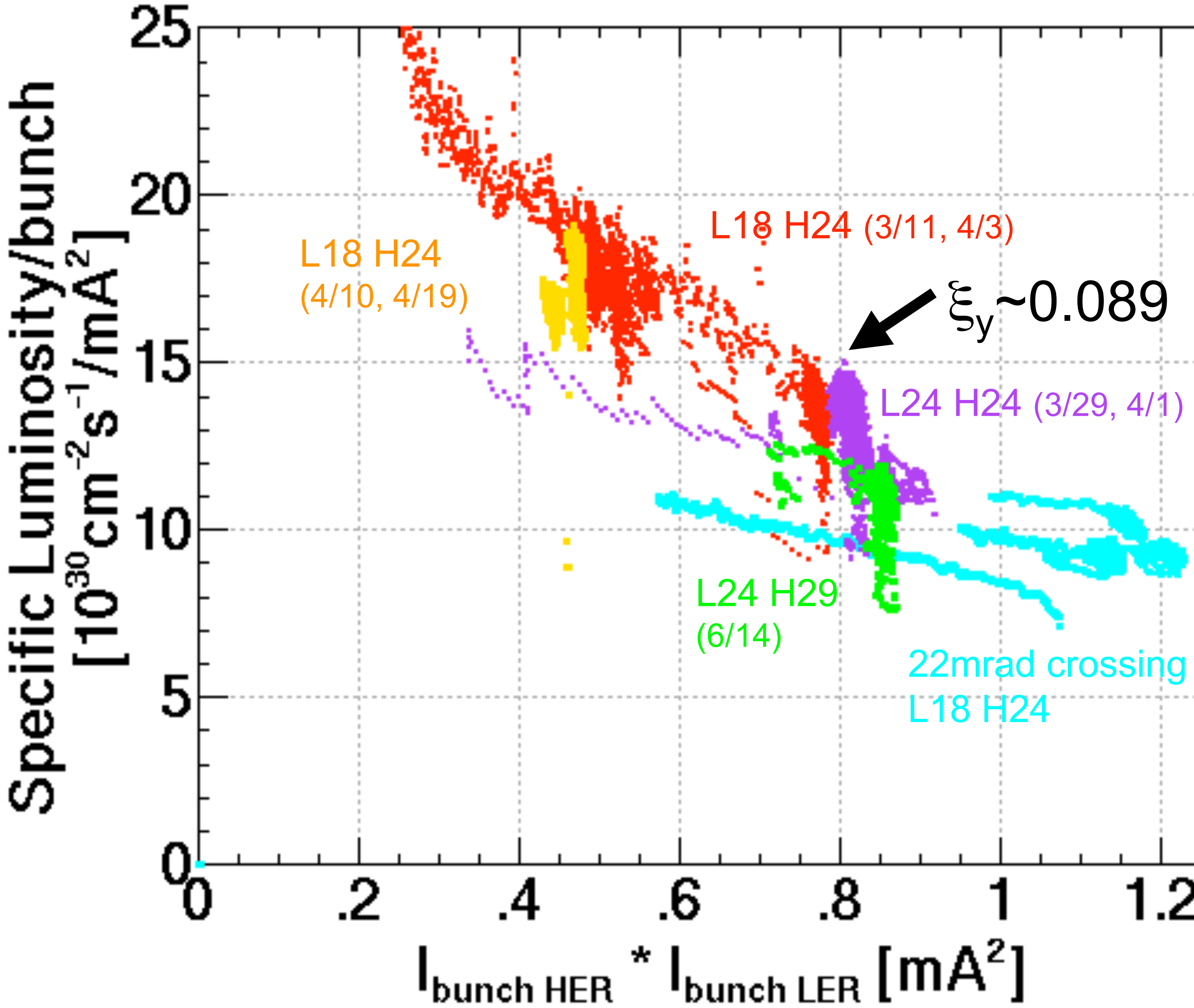
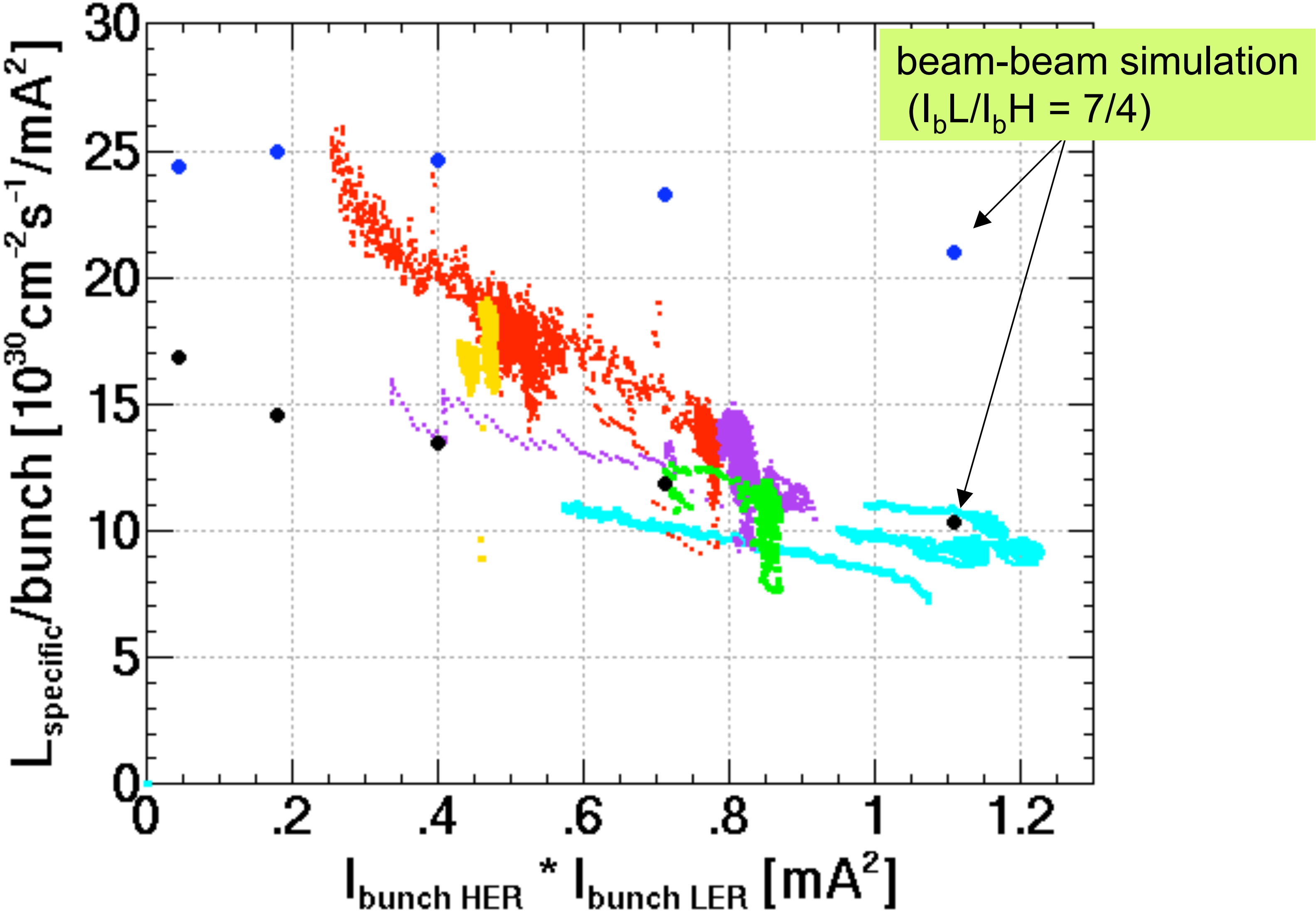
Belle
Dead Time [%]
3/1/2007
4/1
5/1
6/1
Recovery of luminosity
LER solenoid off
HER vertical emittance
LER SX search etc.
negative-α
HER high emittance

Luminosity performance with crab

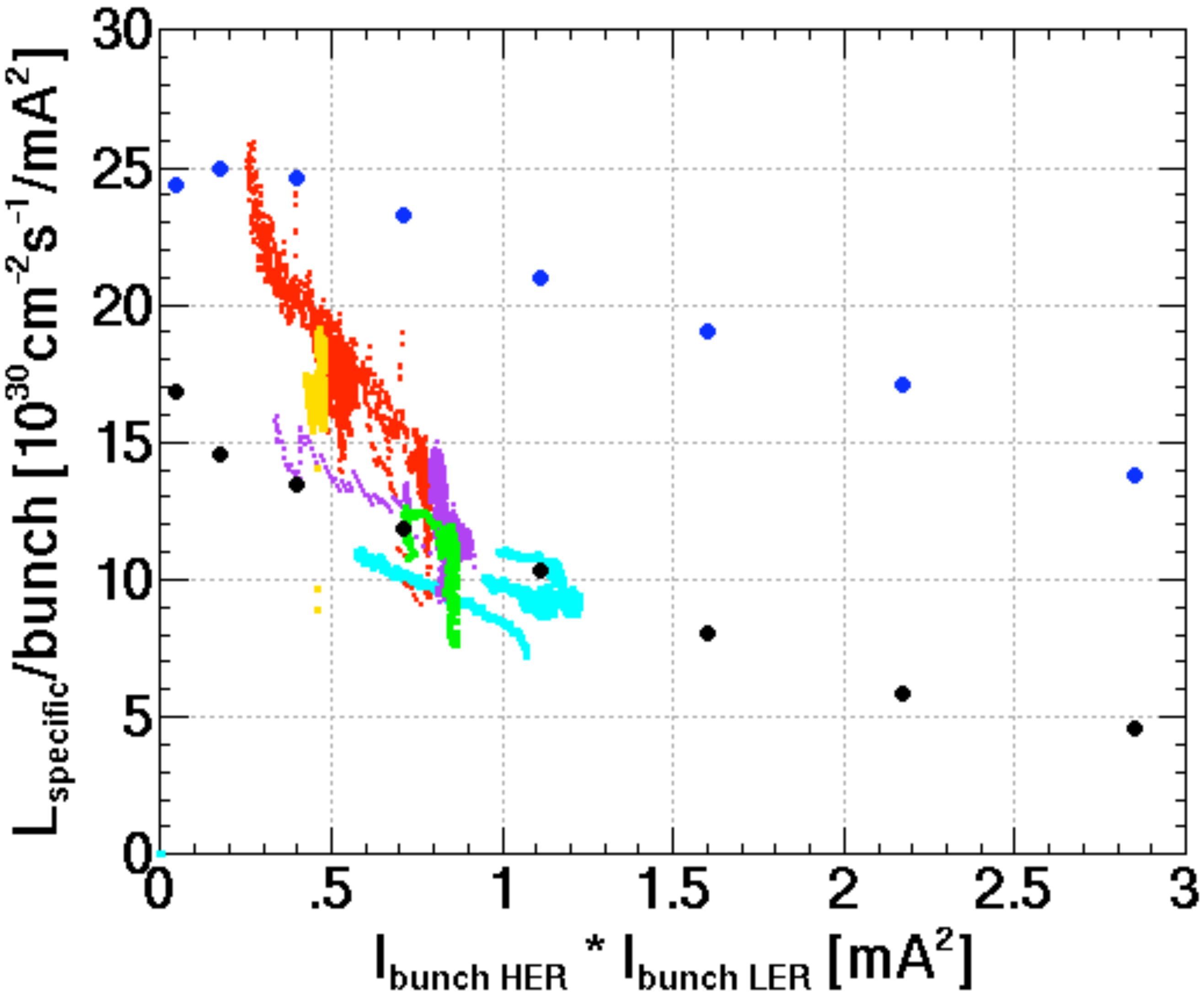
- Specific luminosity
- Beam-beam parameter
- Scaled luminosity

Specific Luminosity



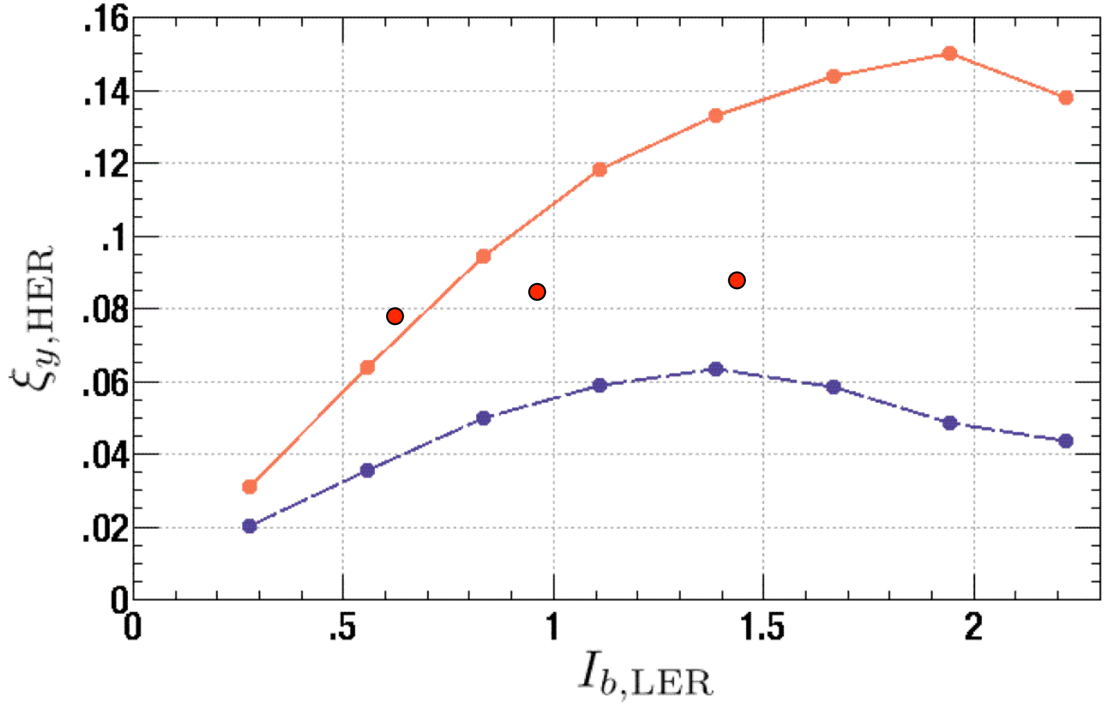


beam-beam simulation
($I_bL/I_bH = 7/4$)
$L_{specific}$/bunch [$10^{30}cm^{-2}s^{-1}/mA^2$]
$I_{bunch\ HER} * I_{bunch\ LER}$ [mA^2]
0
5
10
15
20
25
30
0
.2
.4
.6
.8
1
1.2



$L_{specific}$/bunch [$10^{30}cm^{-2}s^{-1}/mA^2$]
30
25
20
15
10
5
0
0
.5
1
1.5
2
2.5
3
$I_{bunch\ HER}$ * $I_{bunch\ LER}$ [mA^2]

beam-beam parameter with crab crossing (simulation)



beam-beam parameter

$$\xi_y = \frac{r_e}{2\pi\gamma} \frac{N\beta_y^*}{\sigma_y^*\left(\sigma_x^* + \sigma_y^*\right)} R_{\xi_y}$$

●: experiments

	April 2007 with crab		Nov. 2006 w/o crab		
	LER	HER	LER	HER	
Energy	3.5	8.0	3.5	8.0	GeV
Circumference	3016		3016		m
I_{beam}	73.1	28.4	1662	1340	mA
# of bunches	50+1		1388+1		
I_{bunch}	1.43	0.557	1.20	0.965	mA
Ave. Spacing	59		2.1		m
Emittance	24	24	18	24	nm
β_x^*	80	80	59	56	cm
β_y^*	5.9	5.9	6.5	5.9	mm
Ver. Size@IP	1.1	1.1	1.9	1.9	μm
RF Voltege	8.0	15.0	8.0	15.0	MV
ν_x	.506	.510	.505	.509	
ν_y	.580	.582	.534	.565	
ξ_x	.108	.101	.117	.070	
ξ_y	.096	.089	.105	.056	
Luminosity	0.611		17.12		/nb/s

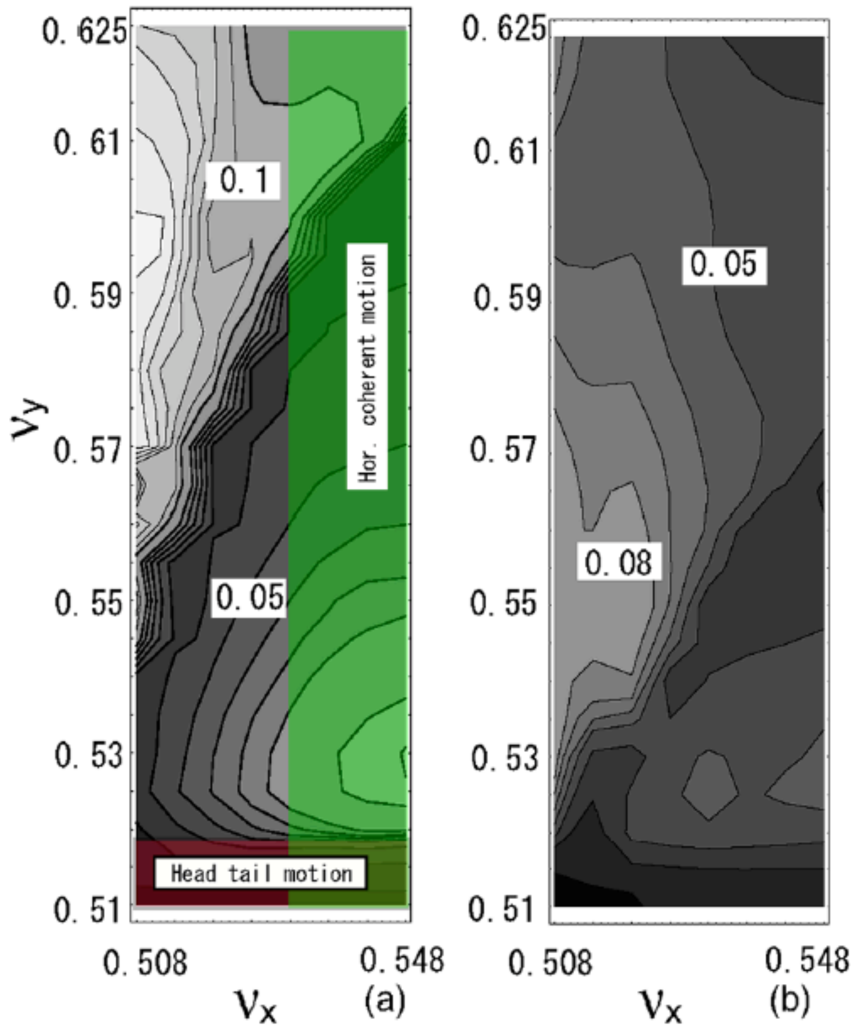


FIG. 6. (Color) Beam-beam parameter ξ_y in x-y tune space. The beam-beam parameter for the crossing angles of 0 and 11 mrad are depicted in (a) and (b), respectively. The contour lines are drawn every 0.01, and lighter gray corresponds to higher beam-beam parameter.

Calculation of beam-beam parameter

- Method of calculation
  - Beam-beam tune shift of the synchronous particle
  - Vertical beam size is calculated from the luminosity.
- Reduction factor for beam-beam parameter

$$\xi_y = R_{\xi_y} \xi_{y0} \qquad \xi_{y0} = \frac{r_e}{2\pi\gamma} \frac{\beta_y^* N}{\sigma_y^* \left(\sigma_x^* + \sigma_y^*\right)}$$

  - 2 sources of reduction
    - hourglass effect and finite crossing angle

$$R_{\xi_y} = \int_{-\infty}^{\infty} \sqrt{1 + \left(\frac{z/2}{\beta_y^*}\right)^2} f_y\left(x, \sigma_x, \sigma_y\right) \rho(z) dz$$

Montague's factor

$$f_y\left(x, \sigma_x, \sigma_y\right) = \frac{k}{k-1}\left[\left(1 - e^{-\frac{x^2}{2\sigma_x^2}} \frac{1}{k}\right) + \frac{i\sqrt{\pi}x}{\sigma_x\sqrt{2\left(1-k^2\right)}}\left\{w\left(\frac{x}{\sigma_x\sqrt{2\left(1-k^2\right)}}\right) - e^{-\frac{x^2}{2\sigma_x^2}} w\left(\frac{kx}{\sigma_x\sqrt{2\left(1-k^2\right)}}\right)\right\}\right]$$

$$k = \frac{\sigma_y}{\sigma_x}$$

$$\rho(z) = \frac{1}{\sqrt{2\pi}\sigma_z} e^{-\frac{z^2}{2\sigma_z^2}}$$

Calculation of beam-beam parameter [cont'd]

- Reduction factor for luminosity

$$R_L \equiv \frac{L}{L_0} = \sqrt{\frac{2}{\pi}}\, a e^{b} K_0(b)$$

$$a = \frac{\beta_y^*}{\sqrt{2}\sigma_z}, \quad b = a^2\left[1 + \left(\frac{\sigma_z}{\sigma_x^*}\tan\phi\right)^2\right]$$

  – Luminosity

$$L = \frac{1}{4\pi}\frac{N^+N^-}{\sigma_x^*\sigma_y^*} f_{col} R_L$$

  – We use calculated values for σ_x^* and calculate σ_y^* and ξ_{y0} from observed luminosity.

Comparison of different emittance

	ε_x=18/24nm (L/H) (Mar.14)		ε_x=24/24nm (L/H) (Apr. 1)		ε_x=24/29nm (L/H) (June 14)	
	Low currents (achieved)	High currents (scaled)	Low currents (achieved)	High currents (scaled)	Low currents (achieved)	High currents (scaled)
# of bunches	51	1389	51	1389	100	1389
I_{LER} (mA)	61	1661	75	2043	125	1736
I_{HER} (mA)	34	924	30	817	74	1028
Luminosity (/nb/sec)	0.594	16.5	0.611	17.0	1.03	14.3

Comparison with and w/o crab

	ε_x=18/24nm With Crab			ε_x=18/24nm No Crab	
	Low currents (2007/3/14)	High currents (scaled)	High currents (scaled)	High currents (achieved) (2007/11/15)	High currents (acieved) (2005/12/25)
# of bunches	51	1389	1585	1389	1585
I_{LER} (mA)	61	1661	1933	1662	1800
I_{HER} (mA)	34	924	1078	1340	1360
Luminosity (/nb/sec)	0.594	16.5	18.8	17.1	15.2

Summary of performance

- Specific luminosity
  - ~30% higher than before crab
- Beam-beam parameter
  - ξ_y: 0.089 (cf. 0.056 w/o crab)
- Extrapolated luminosity to higher beam currents
  - We need to increase the number of bunches.
    - 18.8 /nb/s (1585 bunches with 3.06 spacing)
    - poor beam lifetime

Efforts for improving specific luminosity

- Knob tuning
  - to remove errors which we know
- Other effects?

Tuning knobs

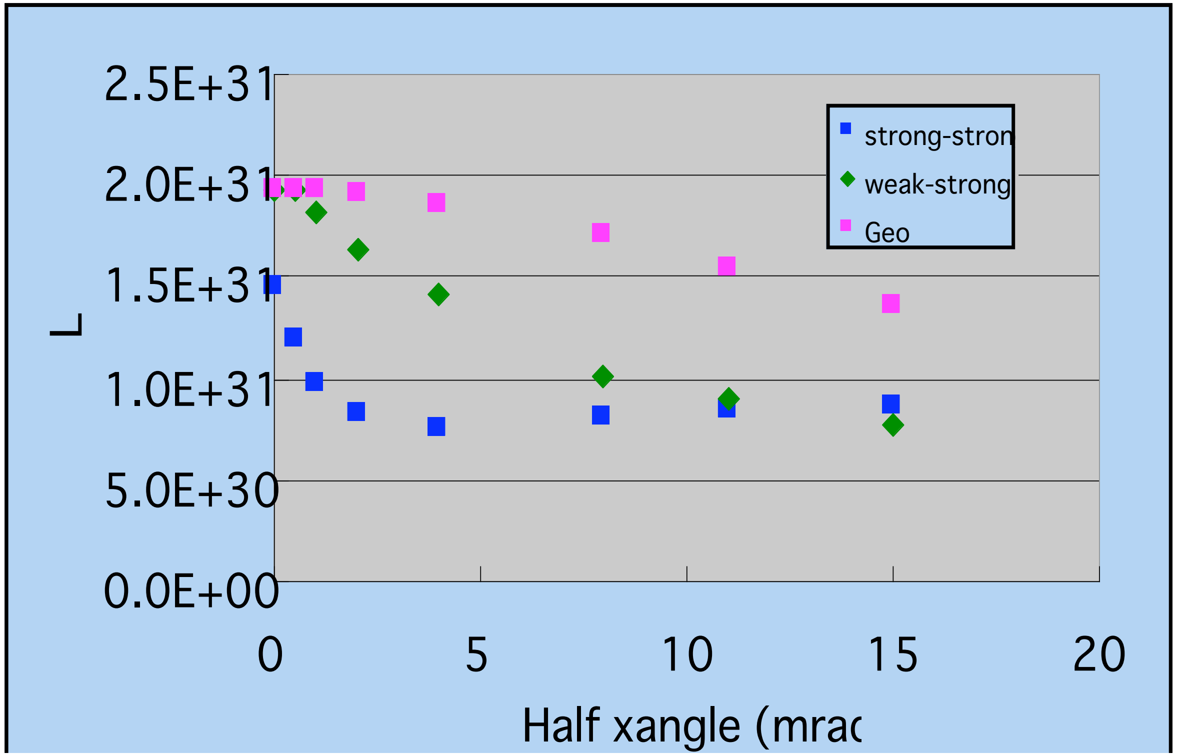
- Legacy tuning knobs
  - iBump v-offset, v-angle, size-target
  - Waist, R1~4 (knob1, knob3), IP vertical dispersion
  - Tune, chromaticity (knob2)
    - Higher vertical tunes bring higher luminosity with crab crossing.
- New knobs
  - iBump Horizontal-offset
  - Crab Vc
  - R2, R4 @Crab (Vertical crabbing)
  - IP Horizontal dispersion
- Tuning method
  - Scan one by one with optimizing mainly the luminosity and sometimes the beam sizes
  - Almost always continued the scans
    - Can we reach the optimum set of parameters with starting unknown errors in the knob parameters? (beam-beam simulation Tawada and Ohmi)
    - Is there a more effective way of searching knobs? -> Downhill simplex method (Oide and Koiso)

Tolerance for errors (simulations by Ohmi et al.)

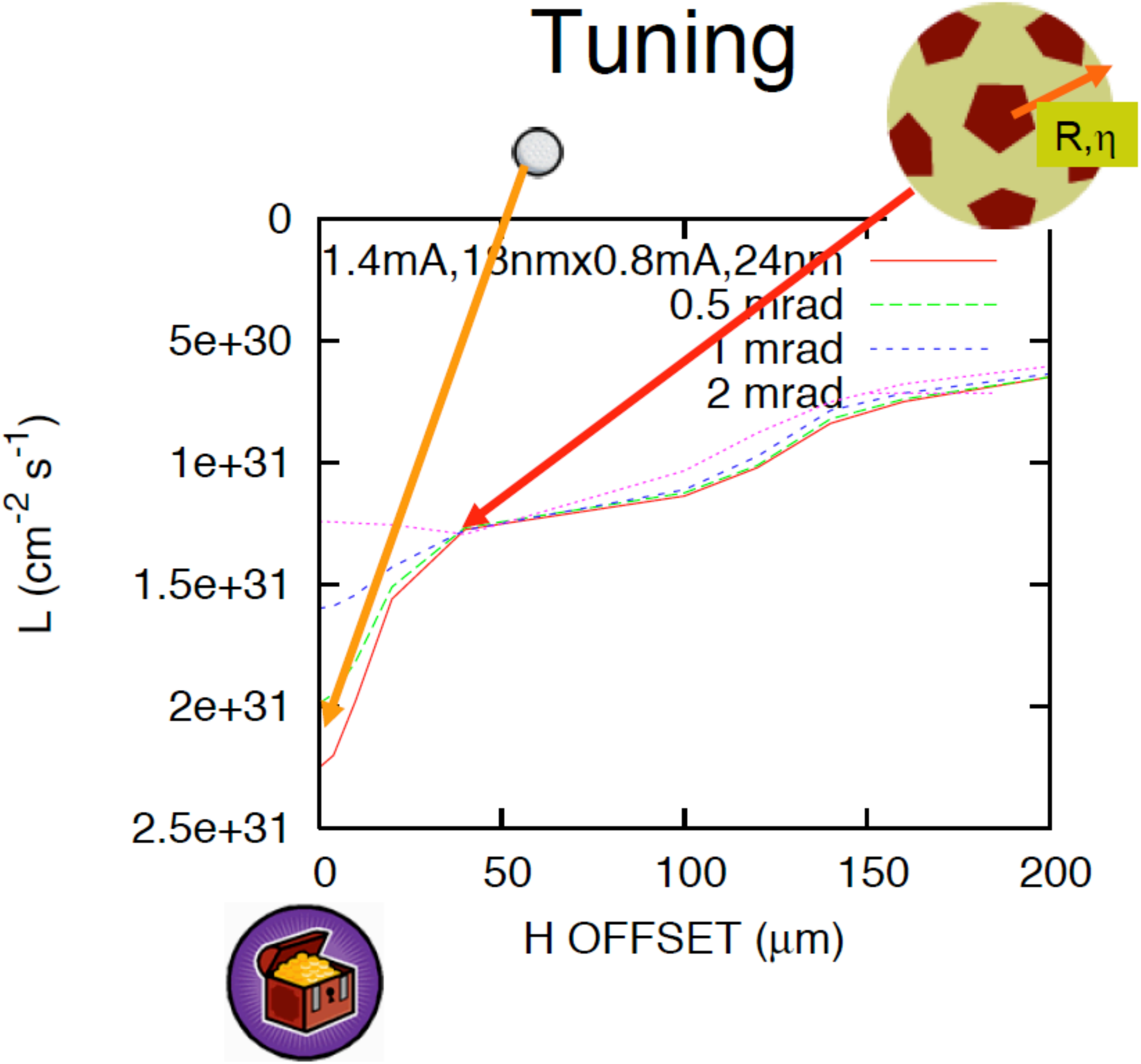
- Sensitive to some errors
  - Horizontal crossing angle
  - Horizontal offset
- Sensitivity to errors of conventional knobs is not so different.
  - IP coupling, IP dispersion, waist

Crossing angle and luminosity

- Sharp peak near zero crossing angle



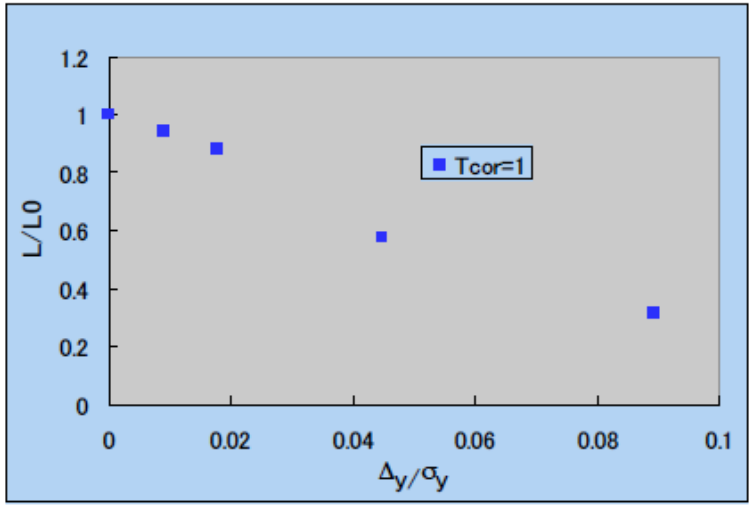
Tuning

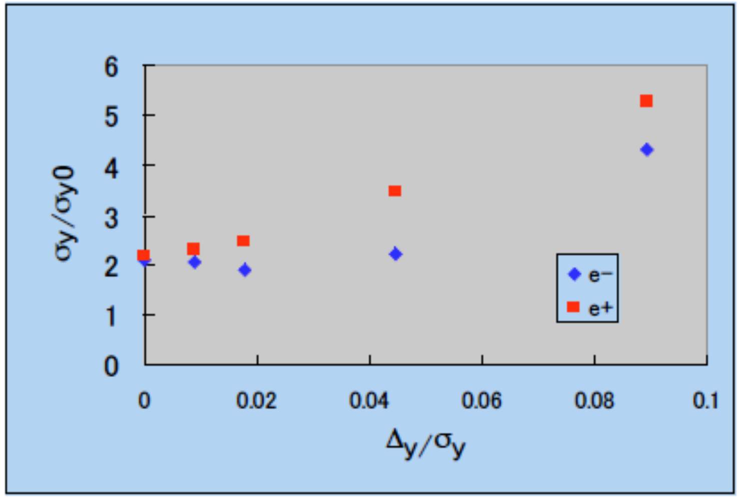

R,η
1.4mA,18nmx0.8mA,24nm
0.5 mrad
1 mrad
2 mrad
0
5e+30
1e+31
1.5e+31
2e+31
2.5e+31
L (cm^-2 s^-1)
0
50
100
150
200
H OFFSET (μm)

External diffusion: Vertical offset noise

- Since the beam-beam system is chaotic, such noise enhances the diffusion of the system.
- Luminosity degradation for the noise without correlation between turns.

$$\langle \Delta y(t) \Delta y(t') \rangle = \Delta y^2 \delta(t - t')$$





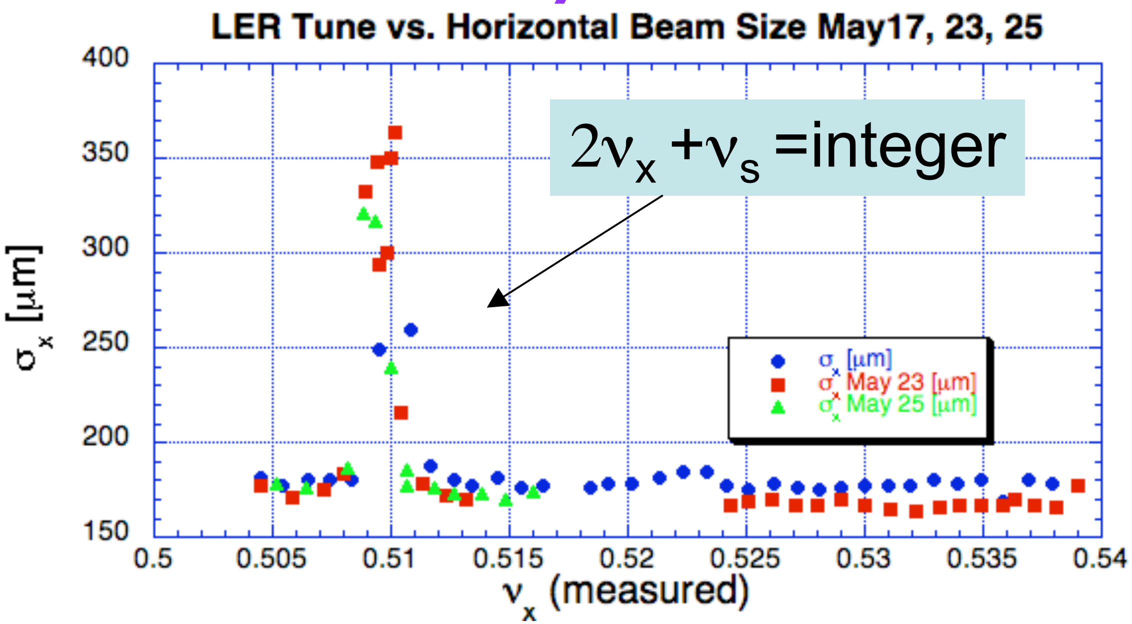
Are there any errors which can not be corrected by usual tuning knobs?

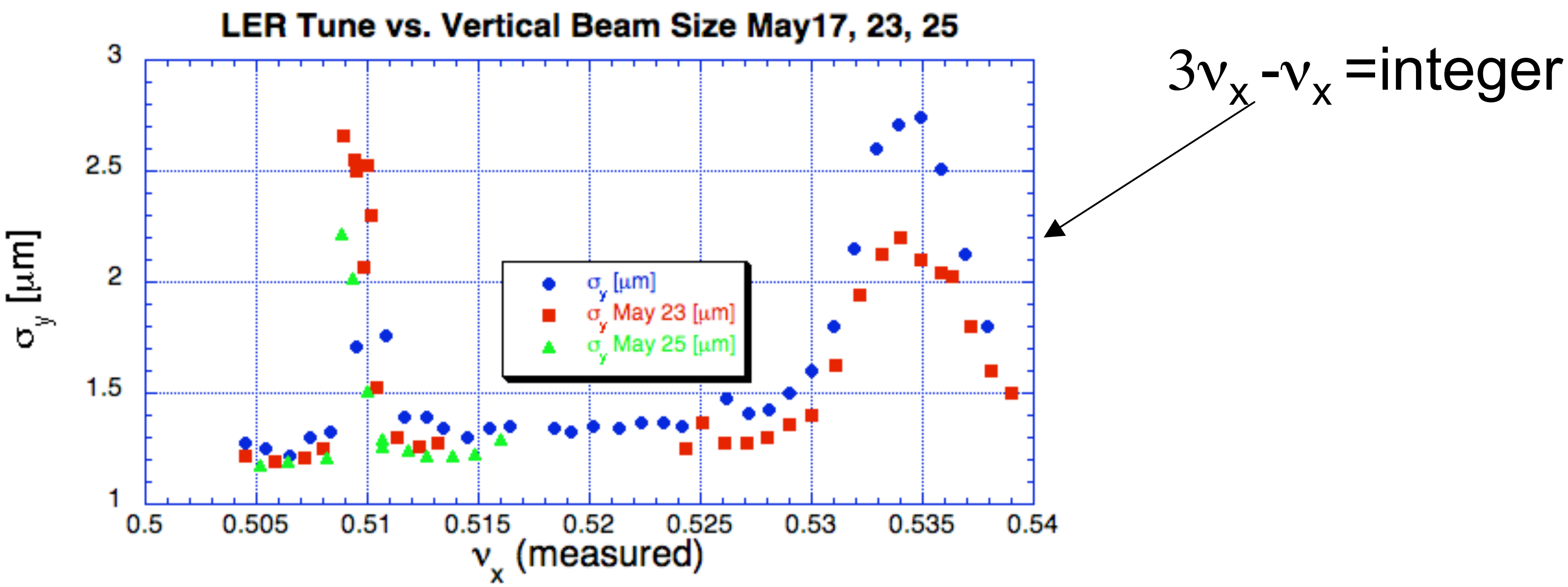
- Effects of synchro-betatron resonance
- What is the source of the anomalous lifetime asymmetry with respect to the sign of the horizontal offset?
- Vertical emittance?
- Bunch length?
- Unknown fast noise？

Importance of SX tuning

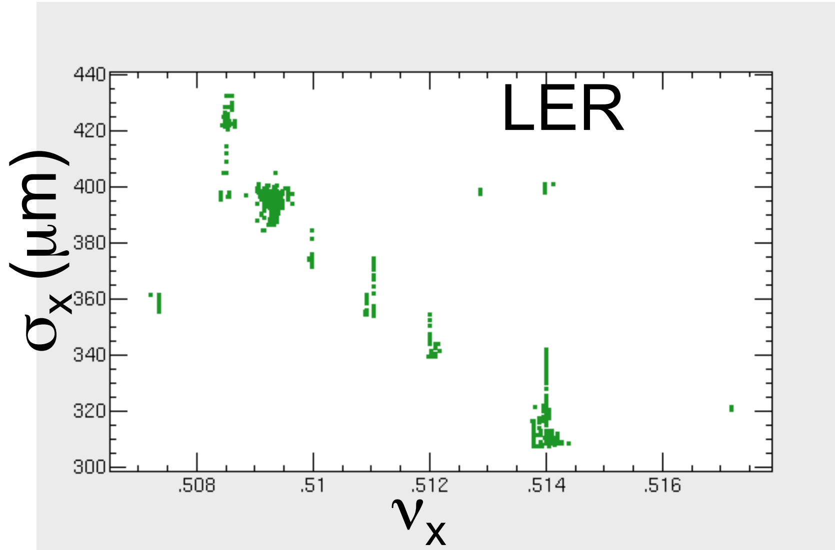
- The choice of Sextuple setting is very importance for the luminosity performance.
- The synchro-betatron resonances ($2\nu_x + \nu_s$ = integer, $2\nu_x + 2\nu_s$ = integer) affect performance.
  - single beam beam size
  - single beam beam lifetime
  - two beam beam size
  - two beam beam lifetime
  - range of betatron tunes that can be used in the luminosity run
- We made a progress both in the method of evaluation of SX performance and the method of SX search in computers (A. Morita).
  - A number of candidates of the SX sets are prepared and tested with the beams from the view point of the beam size blowup and the lifetime decrease at around the resonance lines.

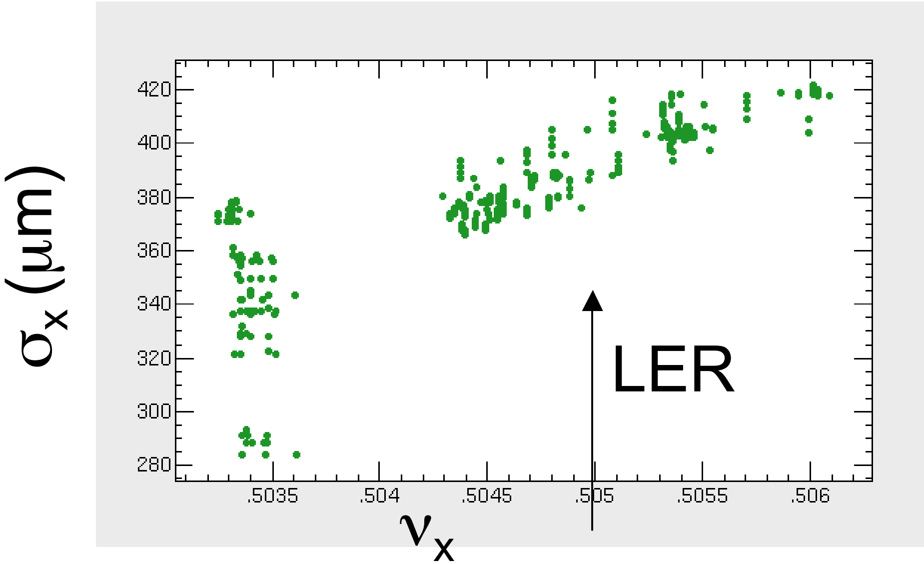
LER σ_x, σ_y tune dependence

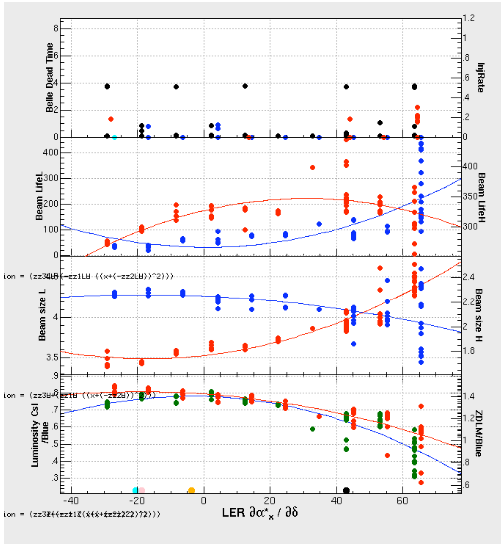




Effect of synchro-betatron resonance on the luminosity





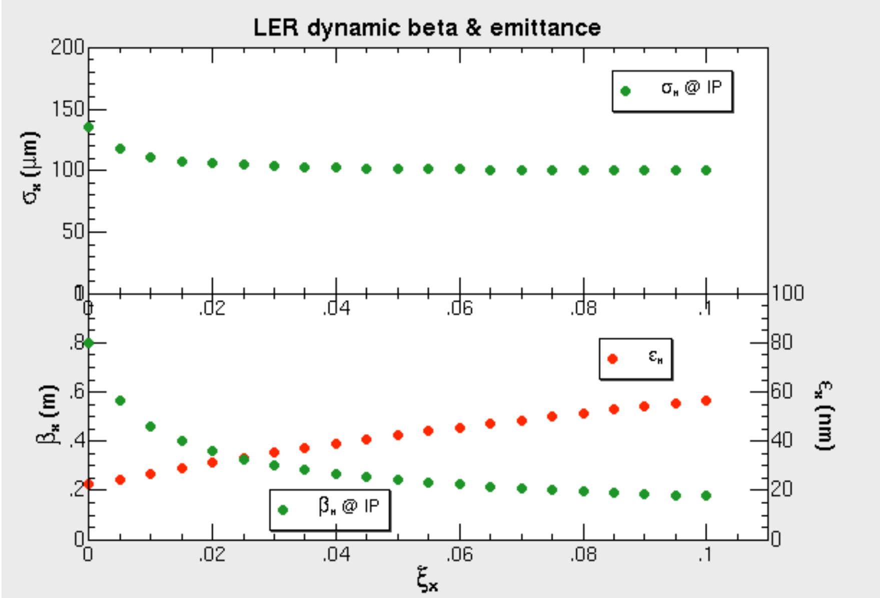


Chromaticity tuning

- We observed the horizontal size changed in the range of 390-330μm.
- The luminosity is improved with the chromaticity tuning.

Dynamic beta and emittance

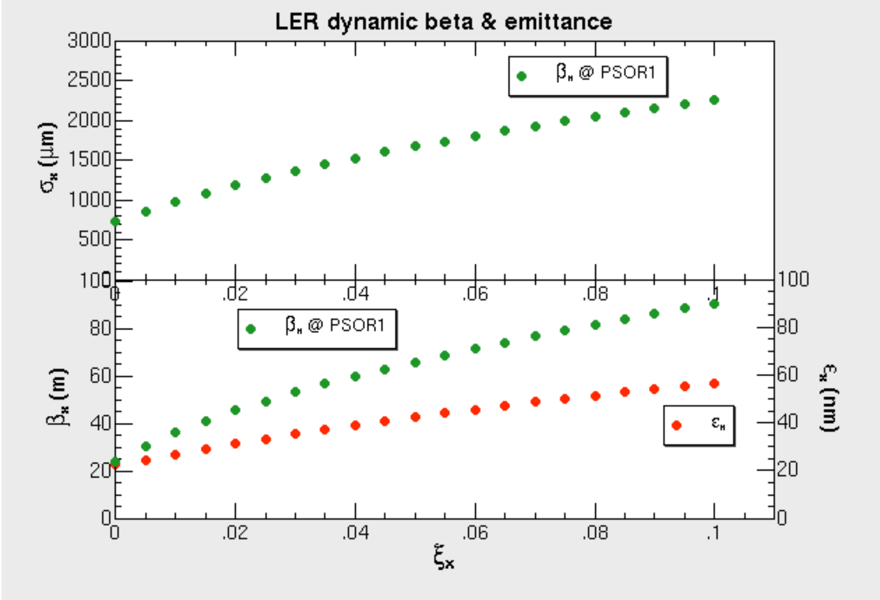
IP



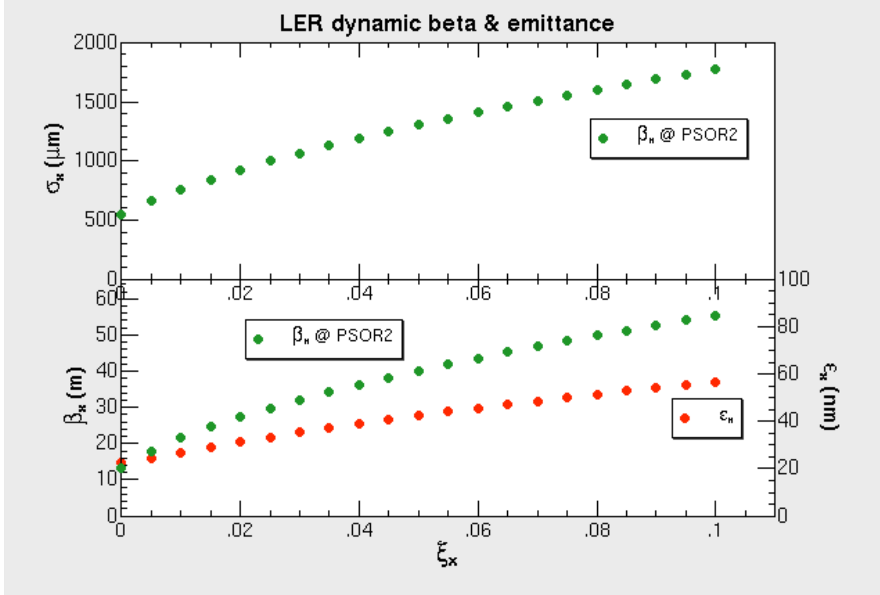
ν_x = .510, ν_y = .580

ε_{x0} =24nm, β_{x0} =0.8m

SRM1



SRM2



Negative-α Optics

- Motivation
  - To weaken the synchro-betatron resonance particularly in HER

    $2\nu_x + \nu_s$ = integer → $2\nu_x - \nu_s$ = integer

    $2\nu_x + 2\nu_s$ = integer → $2\nu_x - 2\nu_s$ = integer

    ν_x: .5112, .5224

    with given $\nu_s \sim -.0224$
  - To shorten the bunch length
- Results
  - We have succeeded to weaken the synchro-betatron resonance line in HER.
  - We have successfully shorten the bunch length of both beam.
    - ~6mm -> ~4.5mm
  - However, we found unexpectedly large synchrotron oscillation in LER and gave up the trial of the negative-α optics.

HER Optics

H. Koiso

Parameter	Positive α (now)	Negative α
ε_x (m)	2.404099E-8	2.408726E-8
ε_y (m)	4.26429E-13	4.26422E-13
ε_z (m)	3.232192E-6	3.257943E-6
α	3.381239E-4	-3.43469E-4
σ_z (mm)	4.83567	4.87357
$\delta p/p_0$	6.684448E-4	6.685162E-4
U_0 (MV)	3.483086	3.483086
$\delta V/p_0$	.021370	.029512
C (m)	3016.262006	3016.262006
Δs (m)	3.689171E-16	3.668473E-16
f (Hz)	508887285.67	508887285.67
Δf (Hz)	6.224168E-11	6.189247E-11
ν_s	-.0224	.0226
$\mathrm{Crabing}_{IP}$ (mrad)	.0000	.0000

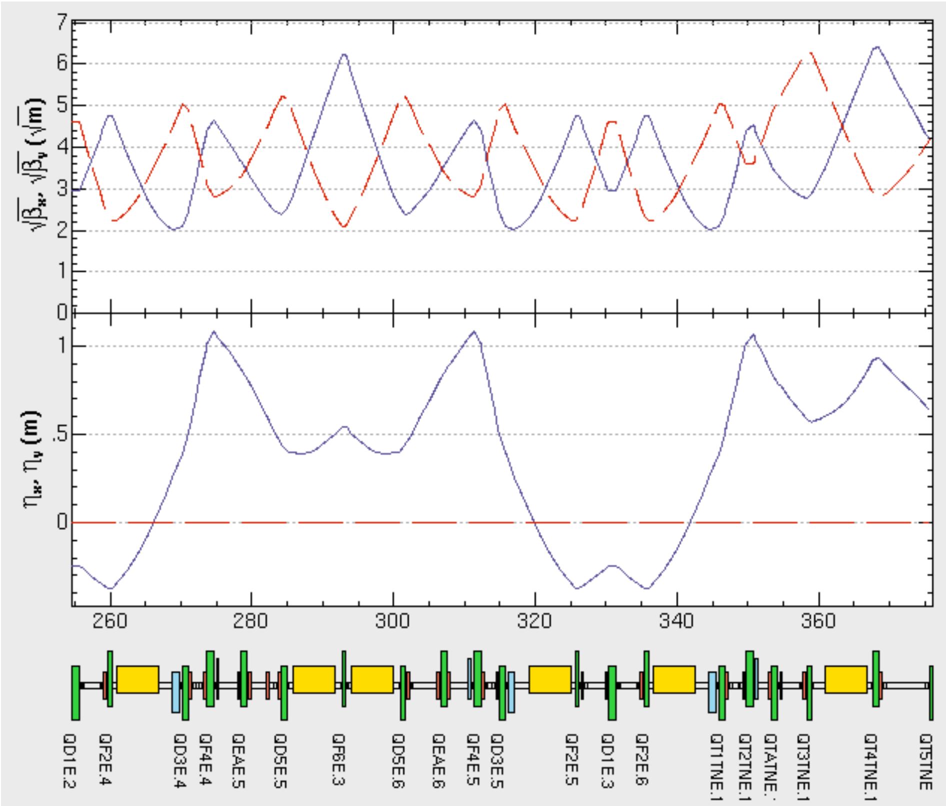
Parameter	Positive α (now)		Negative α	
$\Delta f'$ (Hz)	.0	.0	.0	.0
V_c (MV)	15.00000	15.00000	-15.0000	-15.0000
V_{crab} (MV)	.00000	.00000	.00000	.00000
ϕ_{crab} (deg)	.000	.000	.000	.000

Positive α (now)

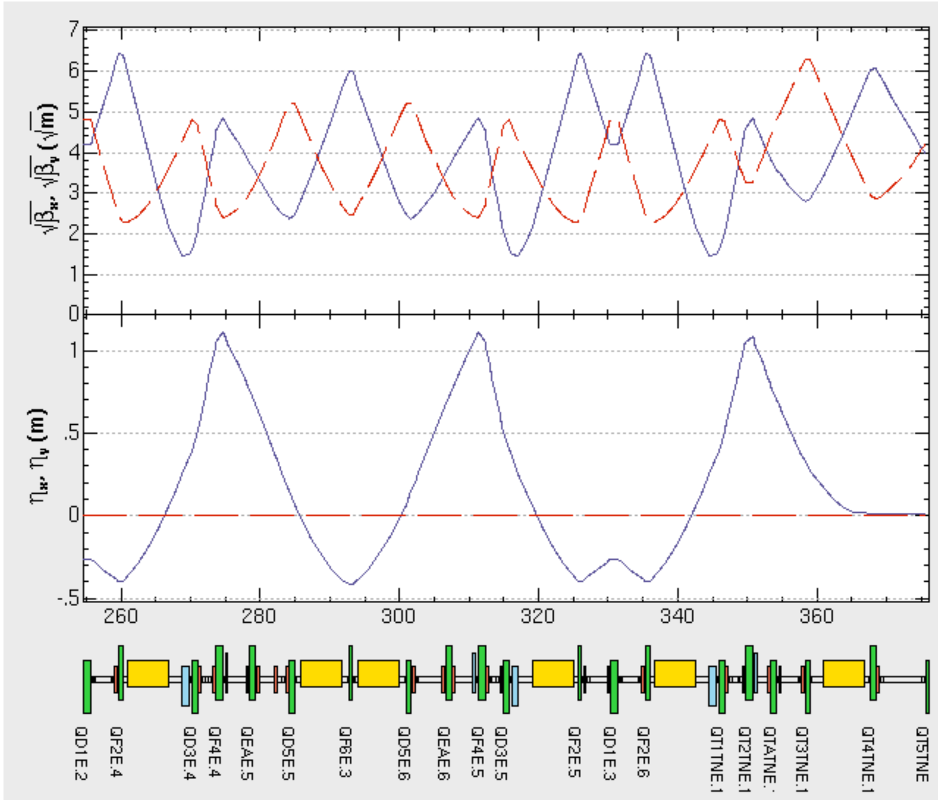
Negative α

HER Optics (cell)

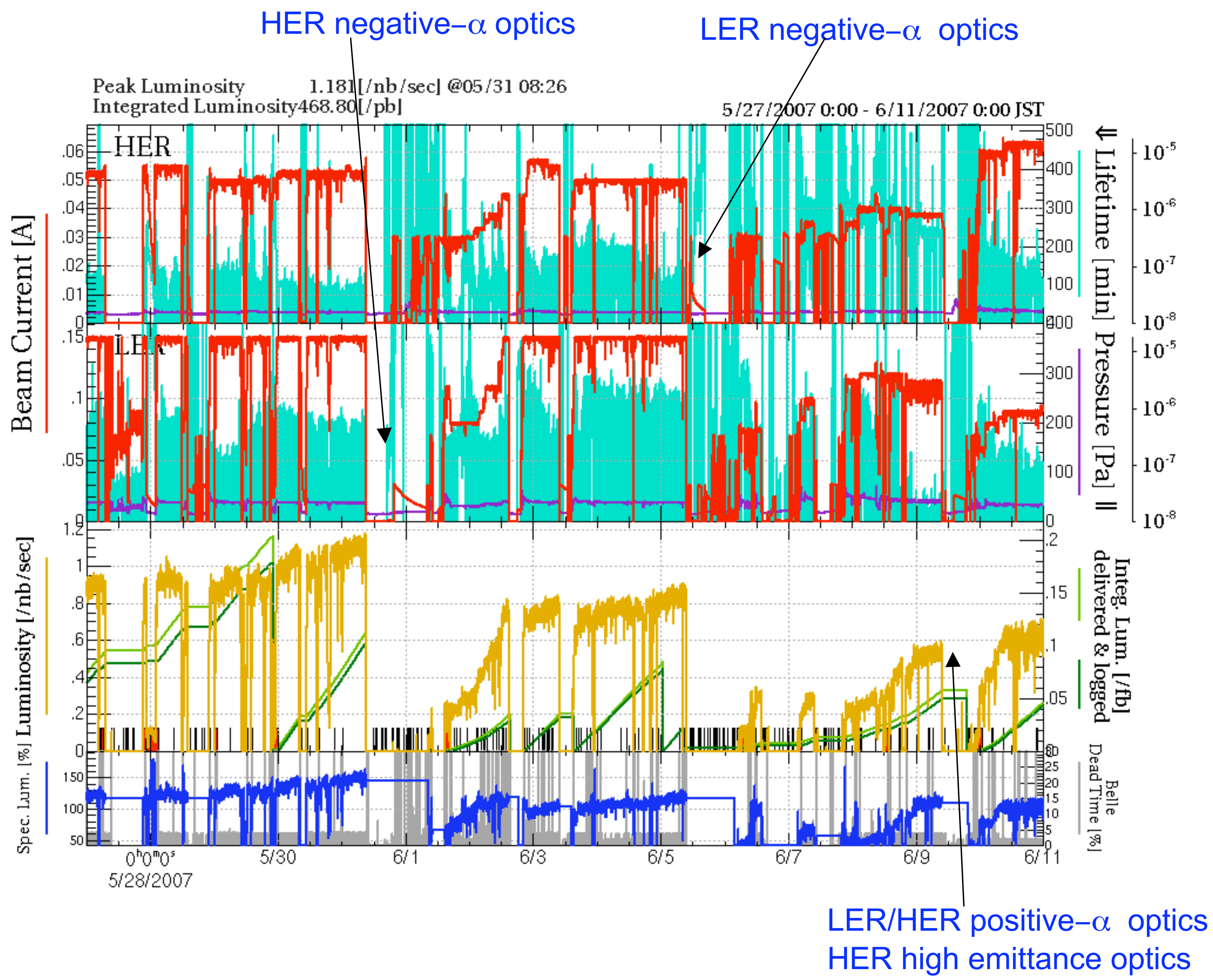
H. Koiso



Positive α (now)



Negative α


HER negative−α optics
LER negative−α optics
Peak Luminosity 1.181[/nb/sec] @05/31 08:26
Integrated Luminosity468.80[/pb]
5/27/2007 0:00 - 6/11/2007 0:00 JST
HER
LER
Beam Current [A]
⇓ Lifetime [min]
Pressure [Pa] ⇓
Luminosity [/nb/sec]
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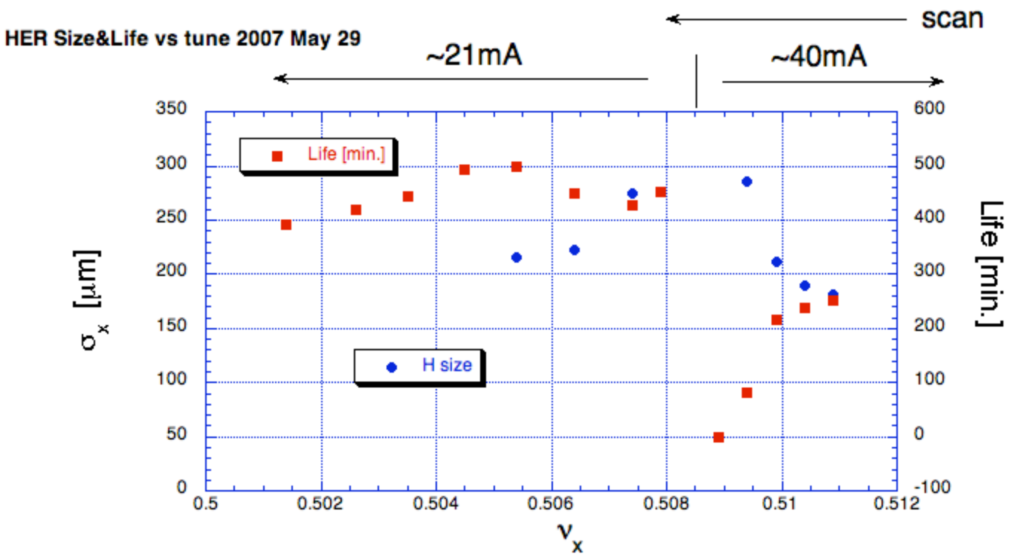
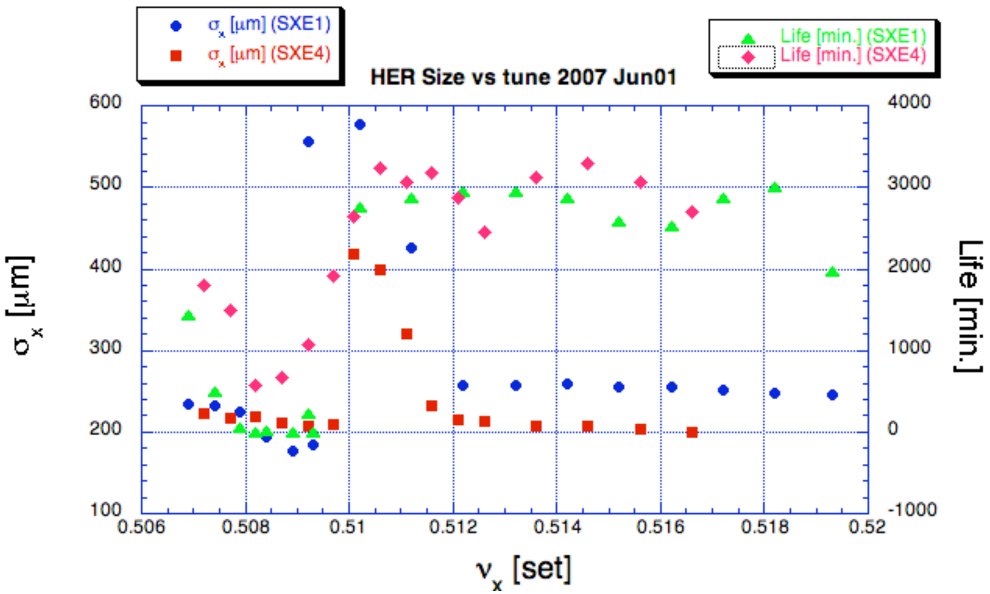
5/28/2007
5/30
6/1
6/3
6/5
6/7
6/9
6/11
LER/HER positive−α optics
HER high emittance optics

Synchro-betatron resonance in HER



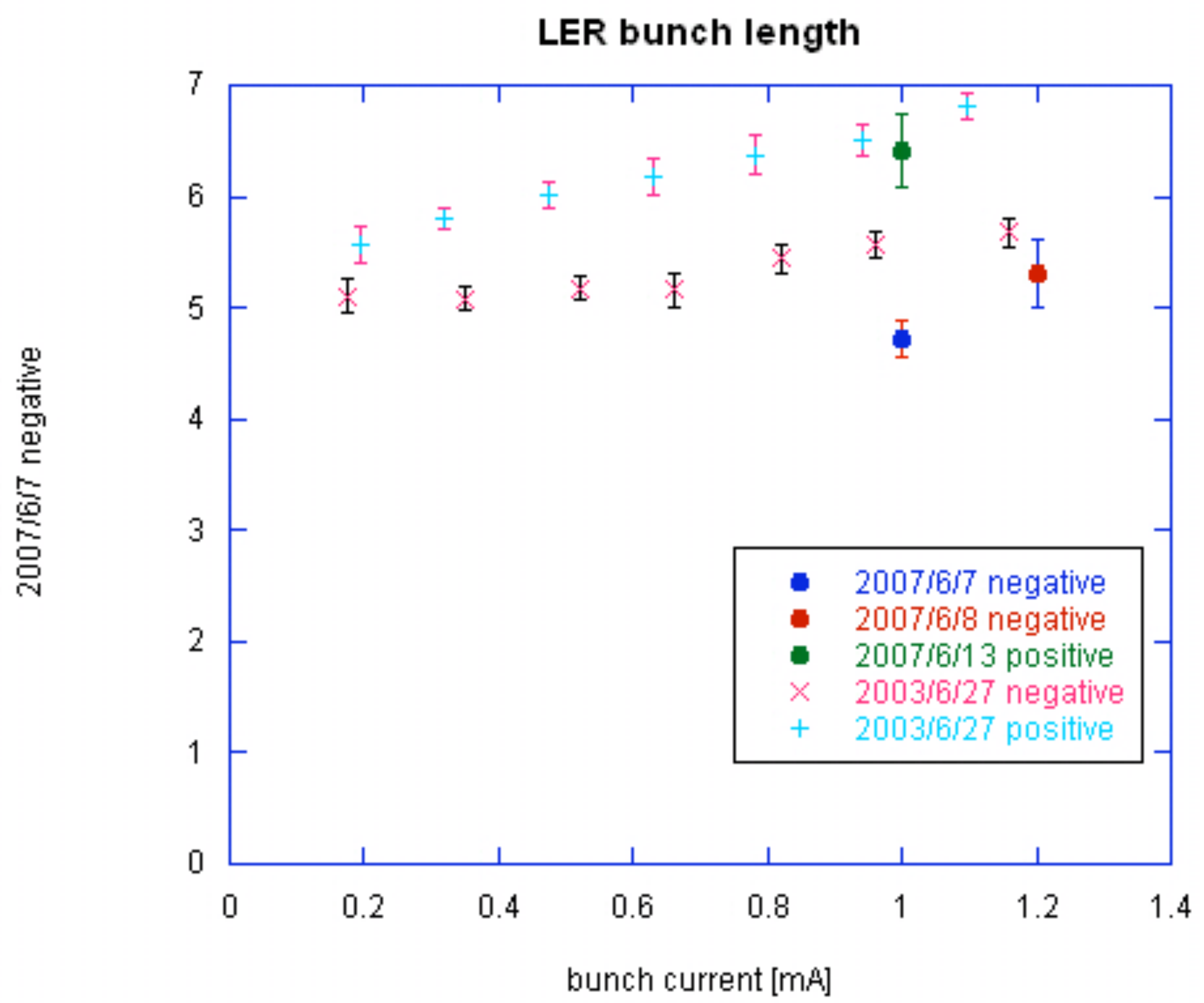
- Positive-α
  - We could NOT operate under the resonance ($2\nu_x+\nu_s$=integer)



- Negative-α
  - We could operate under the resonance ($2\nu_x+\nu_s$=integer)

Bunch length

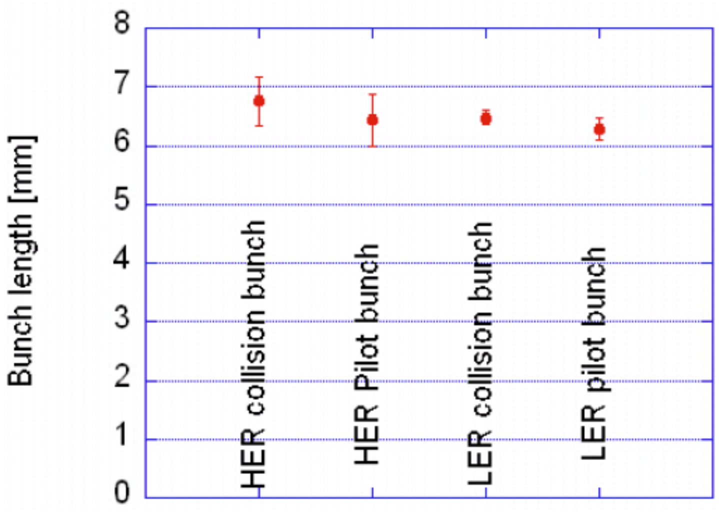
H. Ikeda

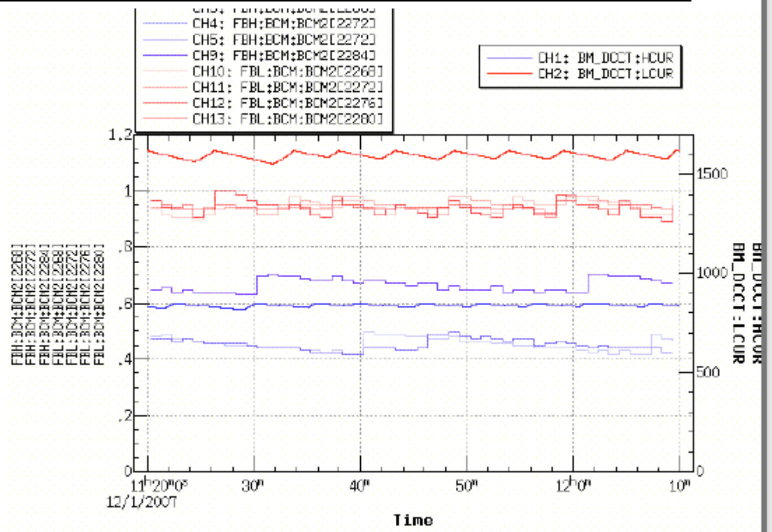


H. Ikeda

071201 bunch length measurement

	HER		LER	
	Collision bunch	Pilot bunch	Collision bunch	Pilot bunch
Bunch length [mm]	6.8	6.4	6.5	6.3
Bunch current [mA]	~0.45	~0.65	~0.95	~0.95
Beam Current [mA]	850		1620	





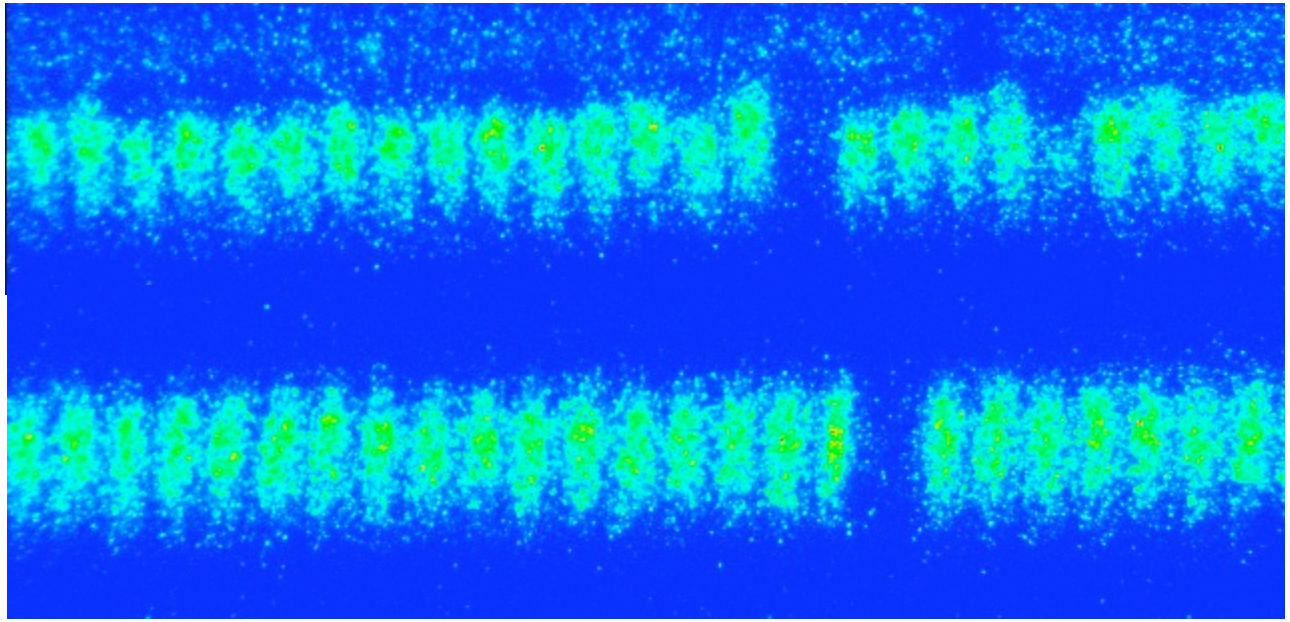
Observation of synchrotron oscillation in LER

- Not the coupled bunch instability but the single bunch instability
  - Observed with single bunch beam
  - Not depends on ν_β, ν_s
  - Amplitude is comparable with the bunch length
- Like saw-tooth instability observed in SLAC damping ring?
  - We did not see in the first trial of negative-α in 2003.
  - We need to check the history of the Ring impedance.

Streak camera from H. Ikeda

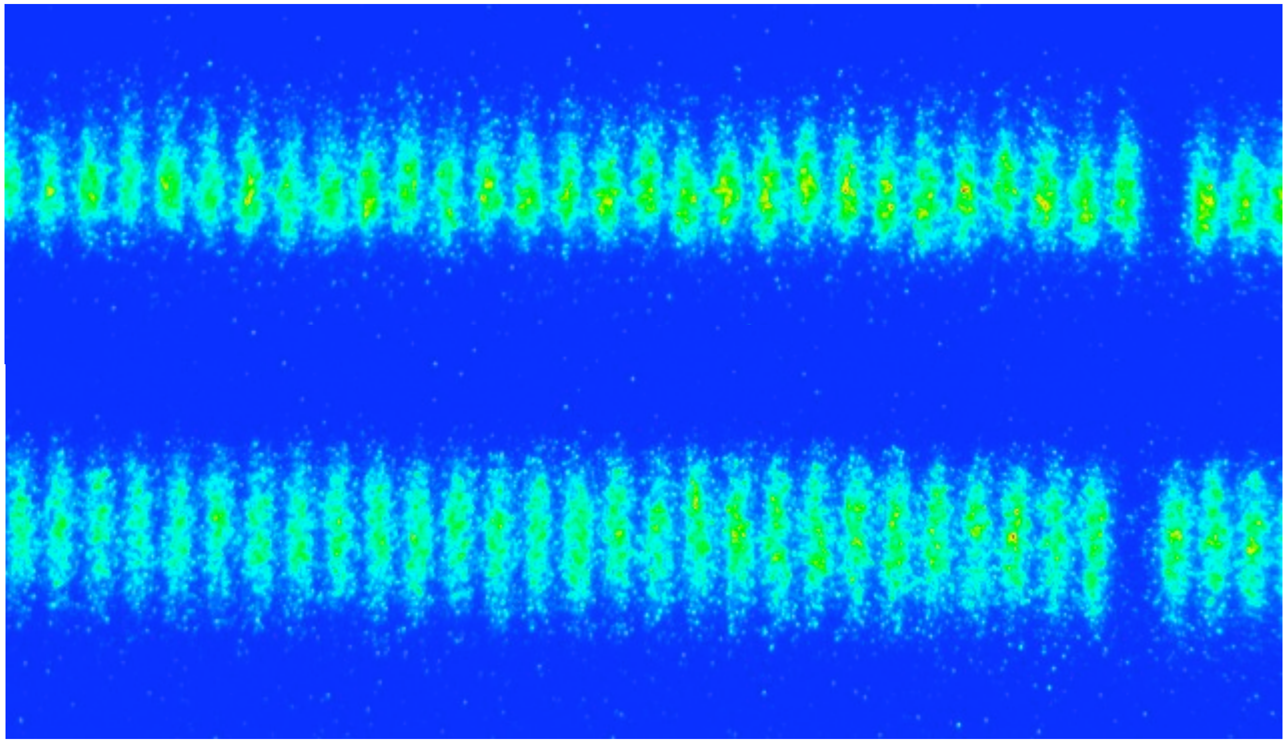
2007/6/8 negative α
Bunch current=1.2mA

2007/6/13 positive α
Bunch current=1.0mA



2003/6/27 negative α
Bunch current=1.16mA

2003/6/27 positive α
Bunch current=1.09mA

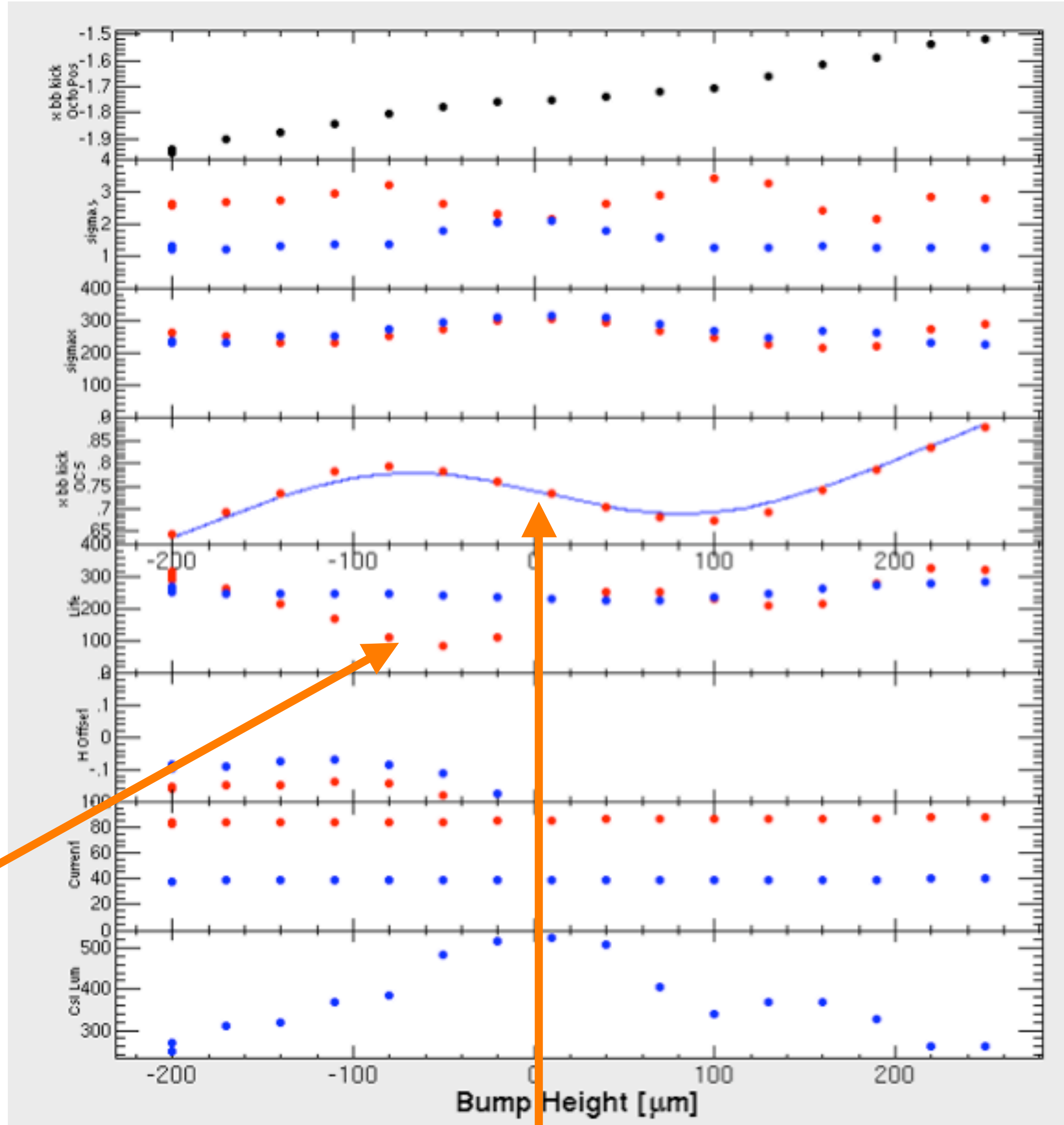


Lifetime issues

- The storable beam currents are limited by poor beam lifetime particularly for the HER beam current.
  - With head-on collision, effective horizontal beam size is larger than with crossing angle.
  - High emittance optics could mitigate somewhat the problem. But its effect was not enough.
  - We need to go for higher number of bunches with shorter bunch spacing.
  - This poor beam lifetime observed is NOT reproduced by beam-beam simulations.
- Lifetime asymmetry with respect to horizontal offset
  - The mechanism has NOT understood yet.
  - It maybe indicate existence of some unknown errors.

Horizontal offset scan

- The (HER) beam current seems to be limited by the short life time of the LER beam.
- The (LER) beam lifetime is very asymmetric with respect to H offset.



LER lifetime

Collision center given by the beam-beam kick

More observations

- “Egure” disappeared with the crab crossing.
- Methods to make a horizontal offset at IP
  - We can make a horizontal offset in three methods
    - make an orbit bump in LER
    - make an orbit bump in HER
    - change collision point in the longitudinal direction
  - The asymmetric nature of the lifetime does not depend on the methods to make the horizontal offset.
- No evidence that the horizontal ring aperture determines the beam lifetime.
- The asymmetric nature does not change even when we enlarge the stronger beam in the vertical direction by making dispersion bumps.
  - The vertical beam-beam tail is not responsible for the poor lifetime?
- The asymmetric nature does not strongly depend on the horizontal tune.

Horizontal offset scan (2004 June 9)

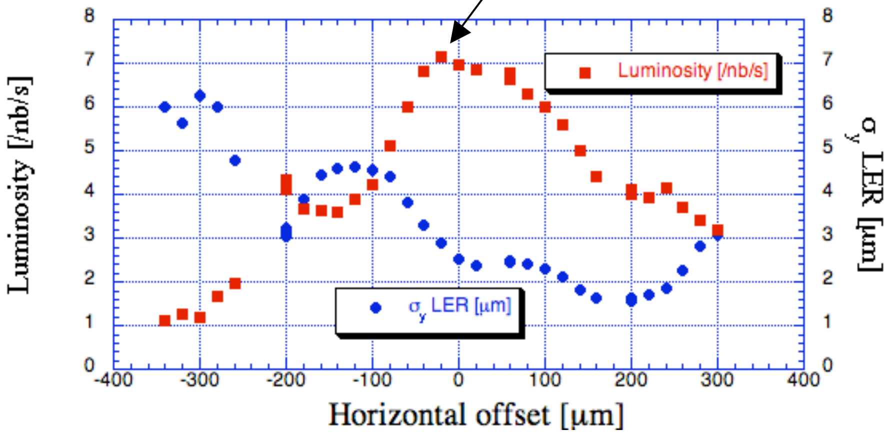
Scan with high current (940mA/1200mA)

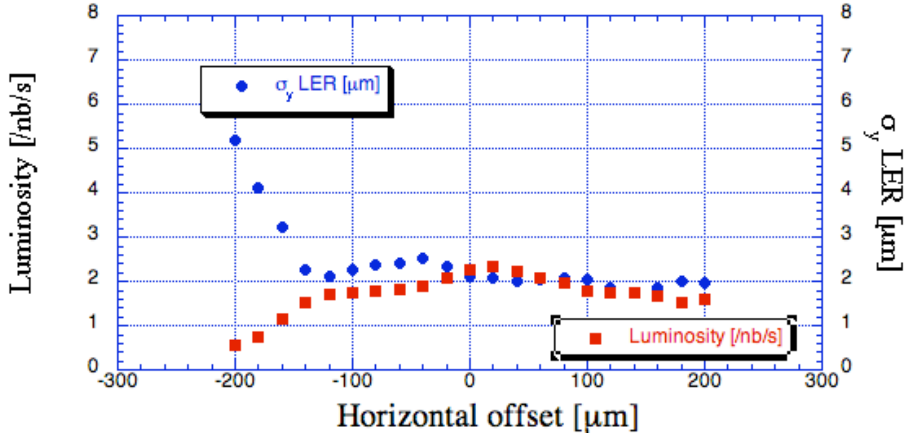
← scan

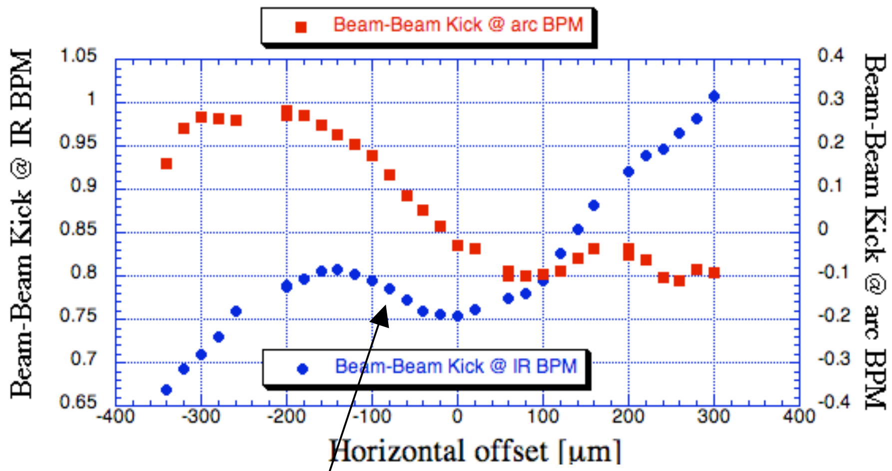
Scan with low current (~400/600mA)

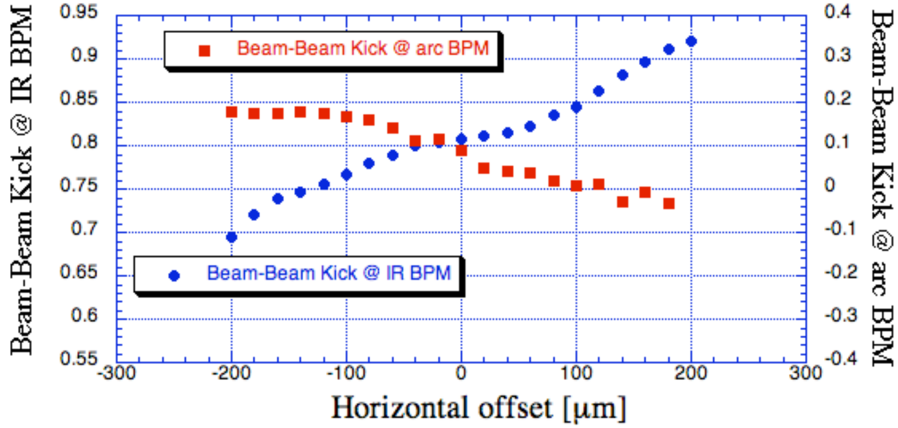
← scan

Lumi peak(H_{set} ~ -20μm)







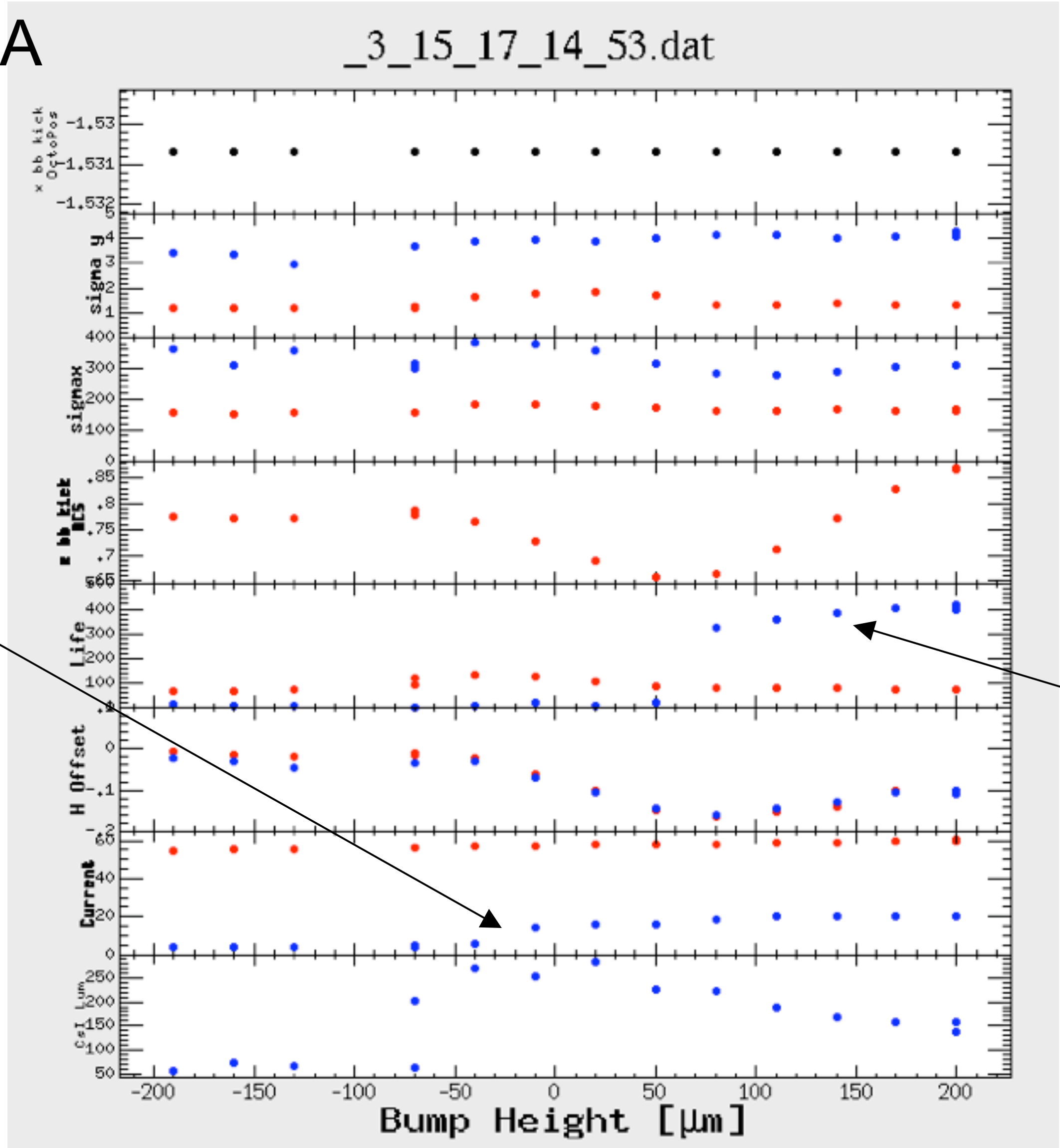


zero-offset (H_{set} ~ -70μm)

Reference data

61mA / 20mA

March 15



HER beam loss

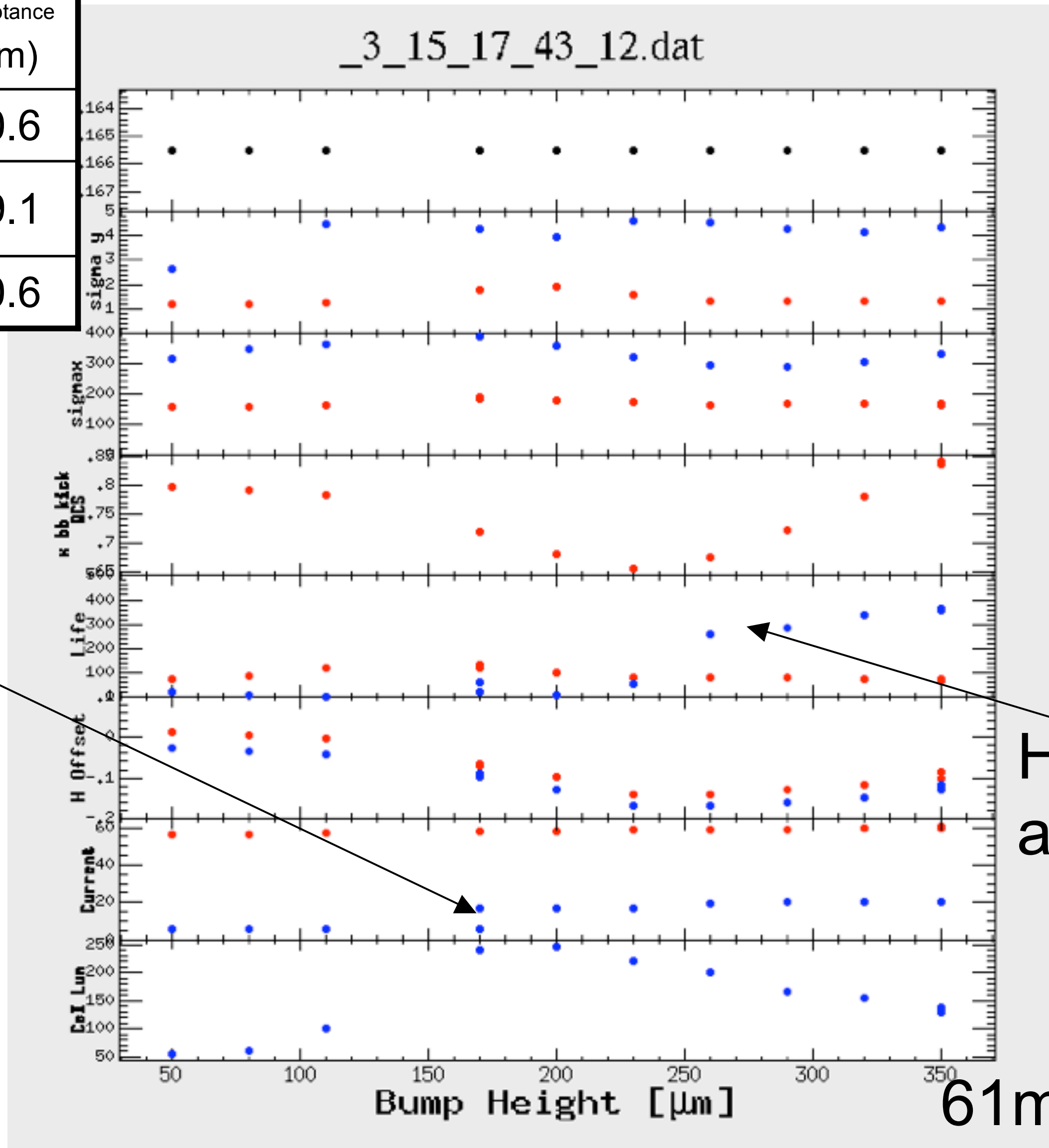
HER life asymmetry

scan direction

With 2mm horizontal bump at Crab in HER

	βx (m)	Aperture (mm)	Acceptance (μm)
crab	174	43	10.6
H-mask	17	18	19.1
Septum	40	35	30.6

March 15



HER beam loss

HER life asymmetry

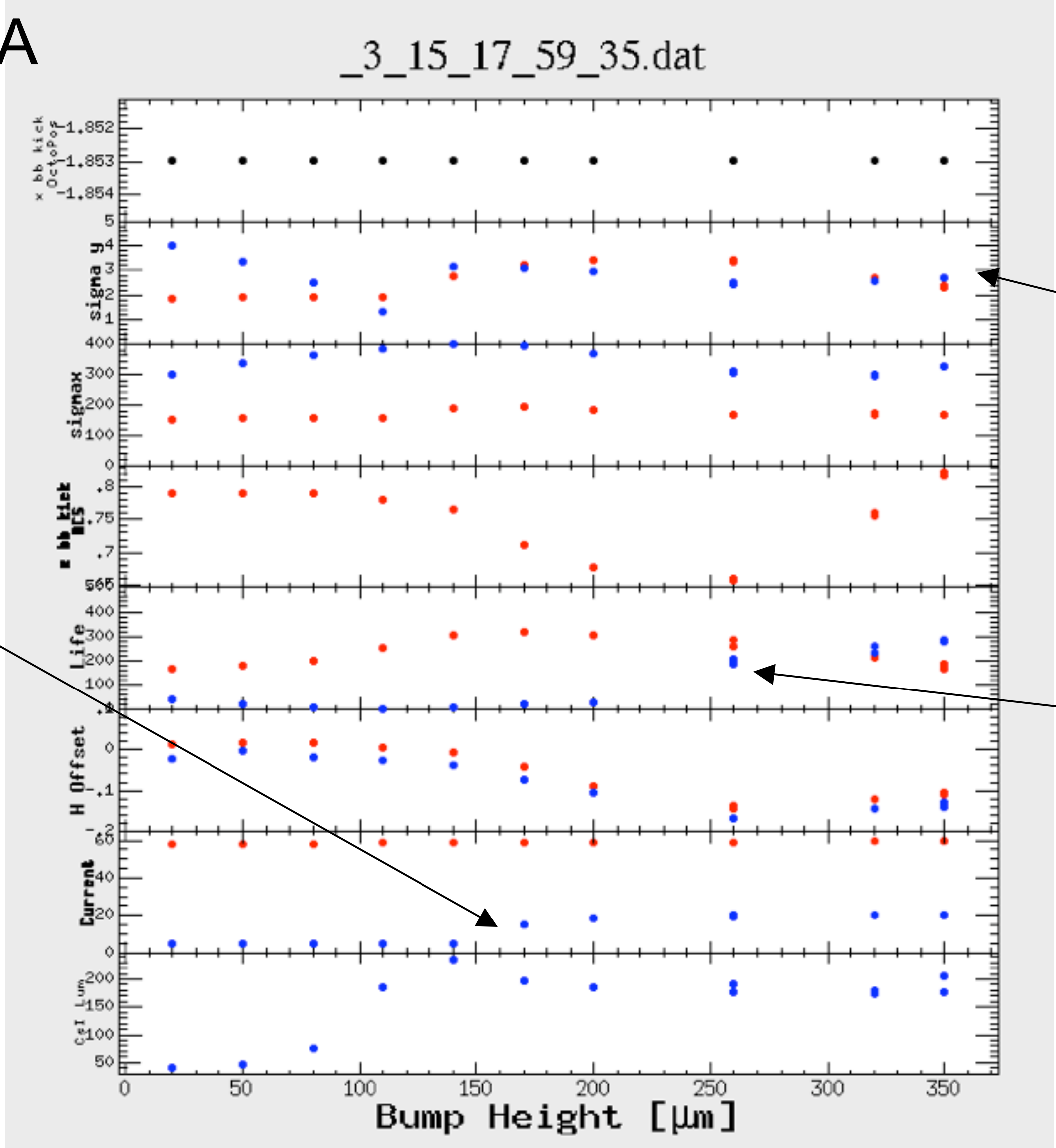
61mA / 20mA

scan direction

iSize Bump(LER) 0 -> 2.4mm

March 15

61mA / 20mA



v sizes changed

HER beam loss

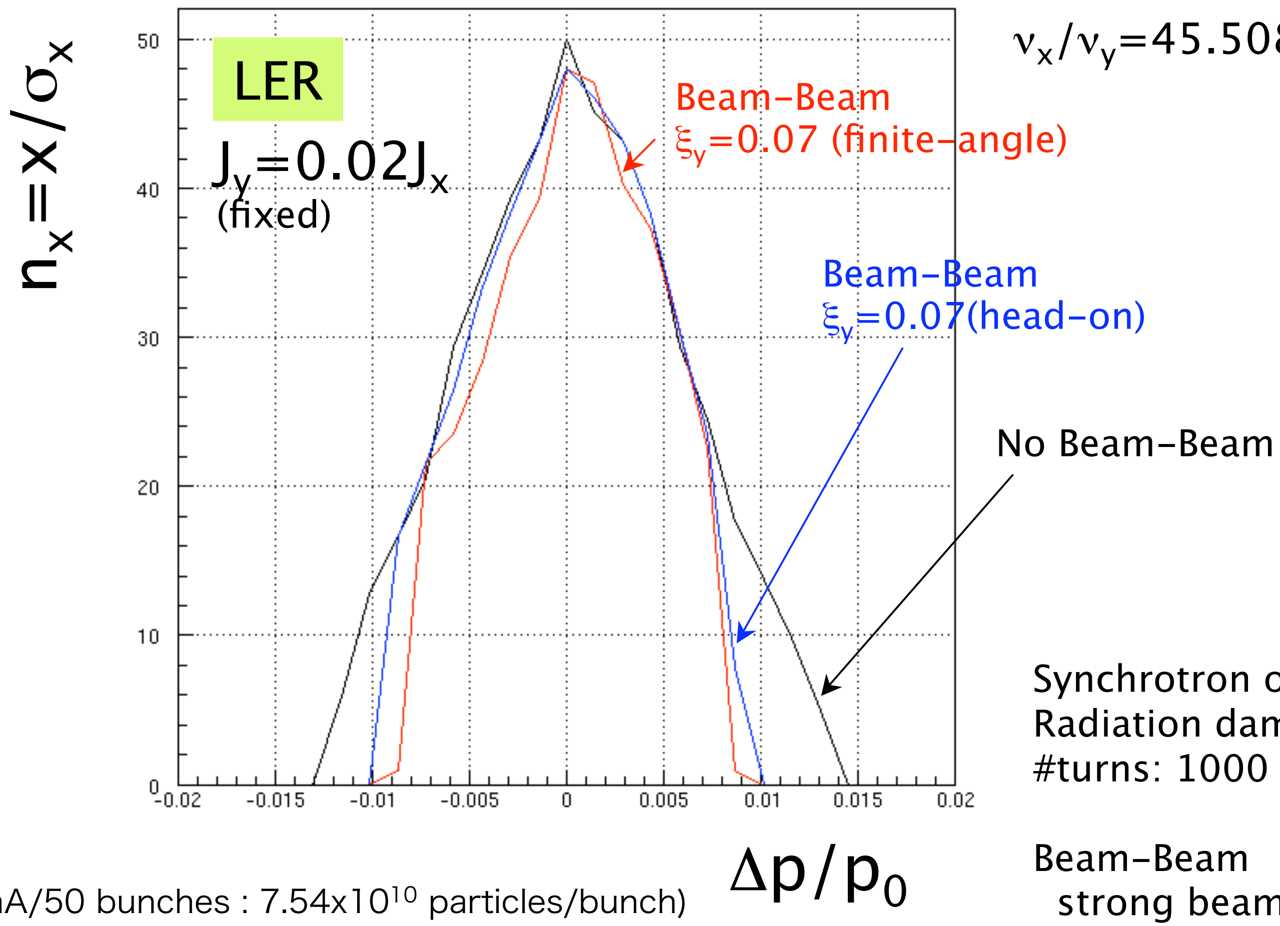
HER life asymmetry

scan direction

Dynamic Aperture of KEKB with Beam-Beam

Off-momentum aperture shrinks due to Beam-Beam effects.

Ohnishi



$\nu_x/\nu_y = 45.508/43.56$

Synchrotron oscillation: ON
Radiation damping: OFF
#turns: 1000

Beam-Beam
strong beam: #slices= 5

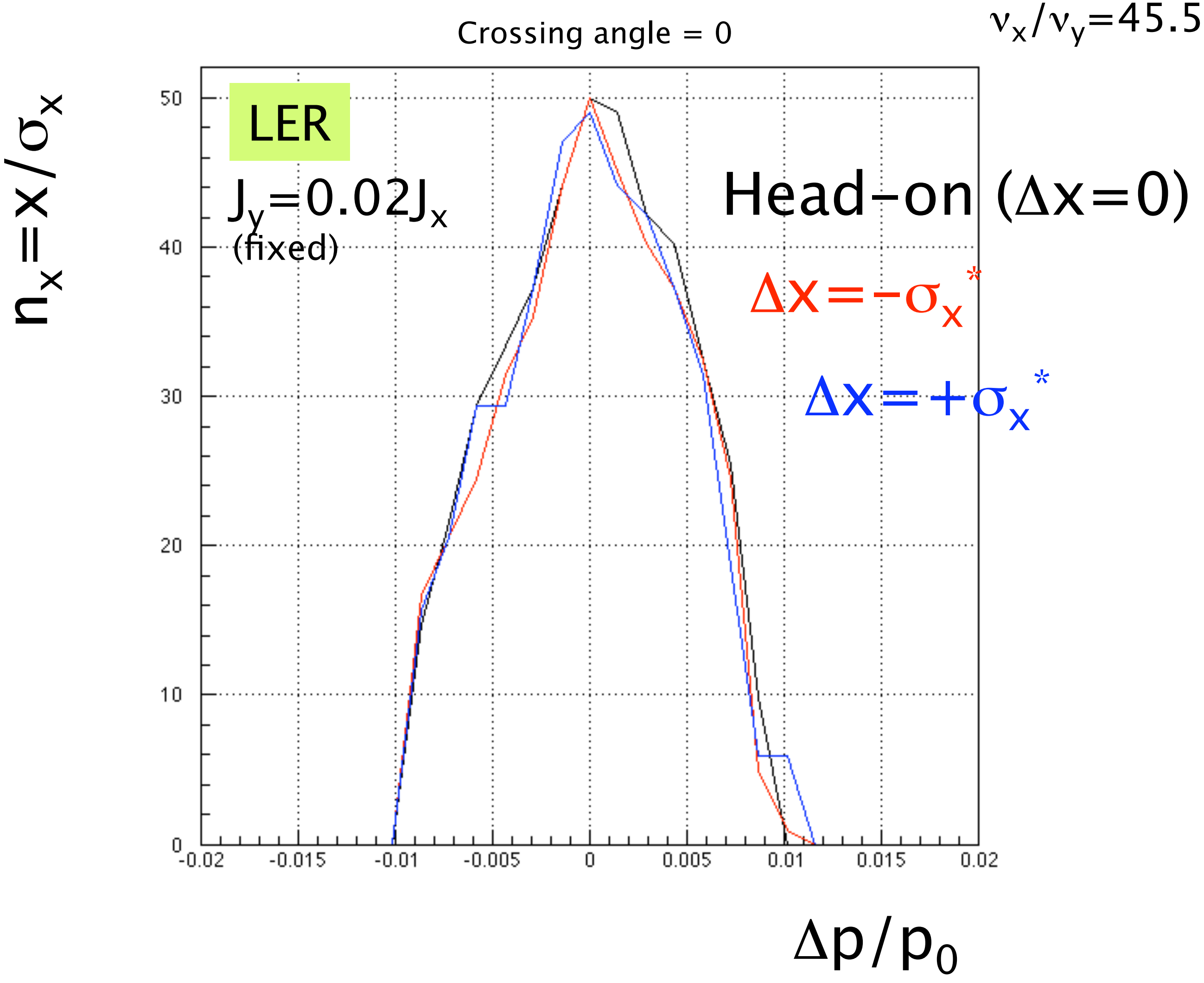
KEKB-LER (60 mA/50 bunches : 7.54x10^{10} particles/bunch)

Coupling (MINCOUP)	2 %
No Beam-Beam	190 min
Beam-Beam(finite-angle)	70 min
Beam-Beam(**head-on**)	88 min

Y. Ohnishi 04/06/2007

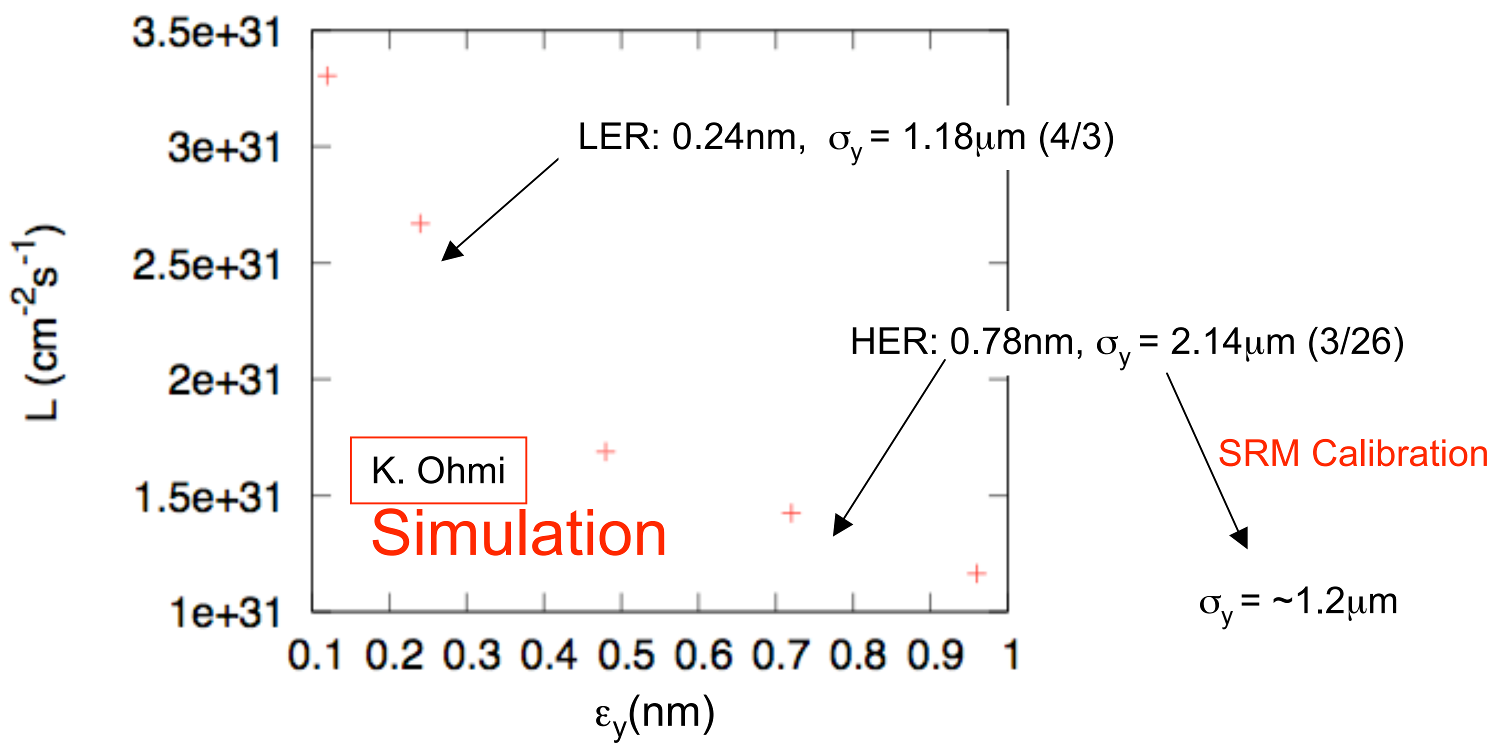
Dynamic Aperture of KEKB with Beam-Beam

ν_x/ν_y=45.508/43.56



Y. Ohnishi 07/04/2007

Vertical emittance (single beam)



- Small vertical emittance always gives better performance.
- Luminosity is saturated to 0.1% before due to flip-flop. This may be due to a small error of code.
- Better simulation should give better luminosity for incoherent effect.

Unknown fast noise?

- Fast orbit fluctuation?
- FB noise?
- Crab kick? (Akai)
- Others?

Fast orbit fluctuation ?

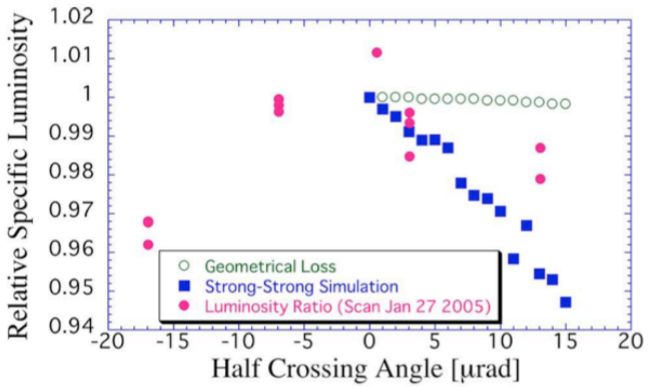
- Fast orbit fluctuation was measured in 1999 and 2000.
  - up to 50 Hz

$$\frac{y}{\sqrt{\beta_y}} \cong 0.002\,[\mathrm{mm}/\sqrt{\mathrm{m}}]$$

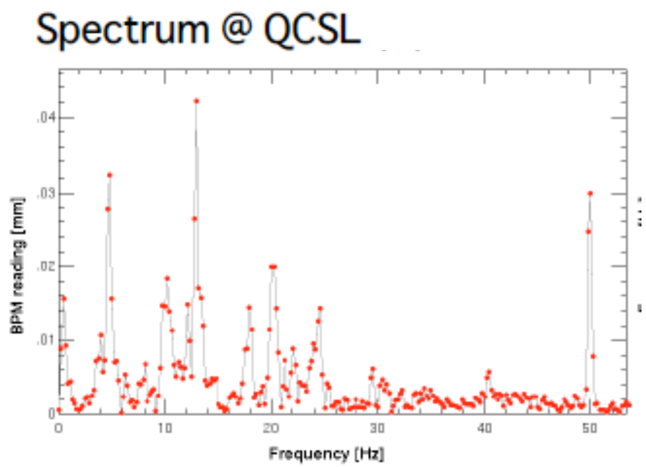
angle@IP not offset

$$\beta_y^* = 10\mathrm{mm}$$

y'@IP $\cong 20\mu\mathrm{rad} \cong 0.015\sigma_y'^*$ ← not very big effect



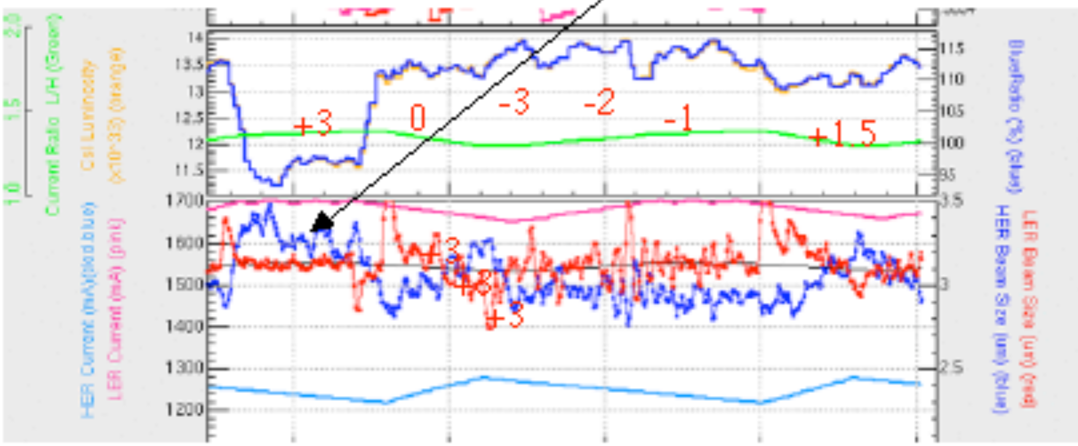
LER vertical1999/Jul.01

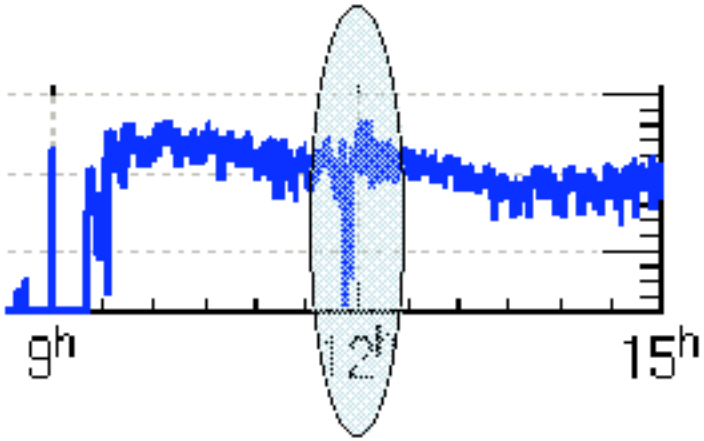


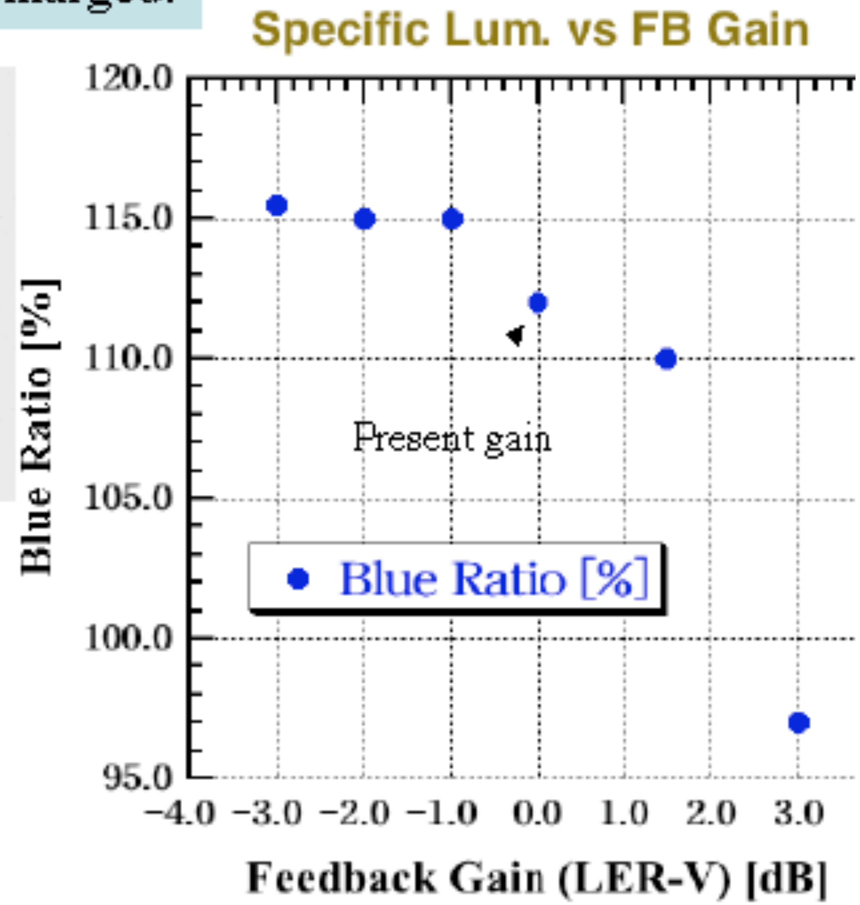
Specific Luminosity vs FB Gain

2005/June/06

HER vertical size enlarged.



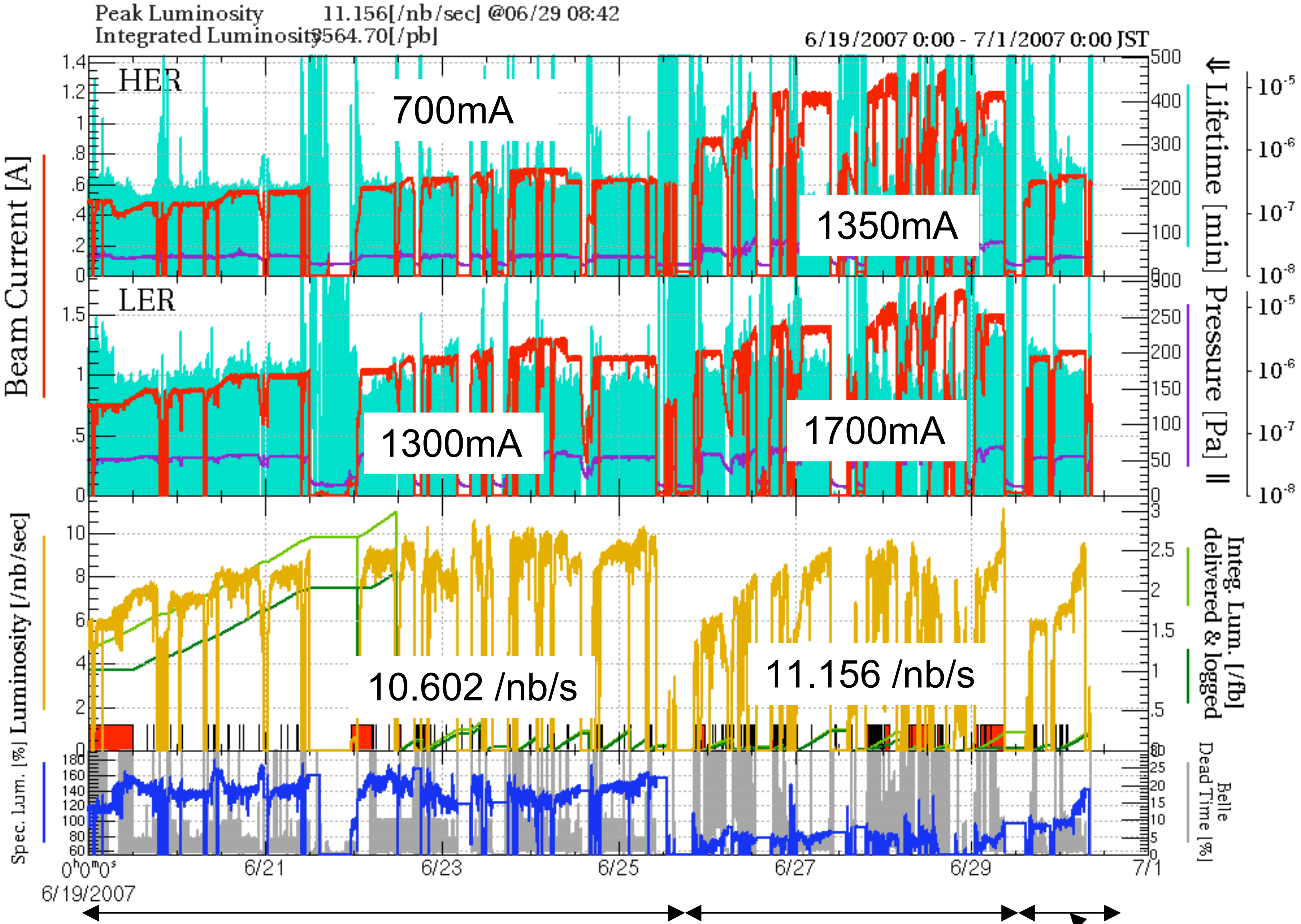




FB gain of the LER vertical affects the specific luminosity.
The other gains (LER H, HER H/V) bring no effects.

High beam current operation with crab cavities

- With crab cavities detuned
  - We could store the nominal beam currents before crab test.
    - 1700mA (LER) and 1350mA (HER)
- With crab cavities on
  - Maximum beam current
    - 1300mA (LER) and 700mA (HER)
    - Trip rate of crab cavities did not seem so serious. -> K. Akai
    - An orbit instability occurred above ~1100mA (LER) in the system of the crab cavities and the horizontal beam-beam kick. -> K. Akai
  - Peak luminosity
    - 10.602 /nb/s <- limited by the orbit instability



Crab ON high currents

Crab detune high currents

Crab ON high currents

Plan for autumn run

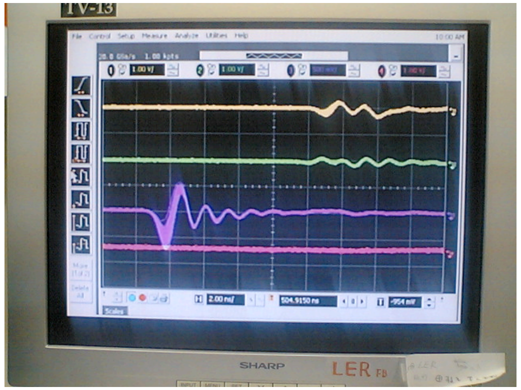
- We proposed the following plan to the Belle group and they accepted.
  - We will start the KEKB operation with the crab cavities turned on and try to increase the luminosity.
  - We assure the Belle group $20fb^{-1}$/month and the accumulation of $80fb^{-1}$ by the end of FY 2007.
  - If achievement of this integrated luminosity is considered to be difficult in spite of our efforts, we will switch to the conventional crossing angle mode with the crab cavities detuned.

spare slides

Observed synchrotron oscillation (single bunch operation)

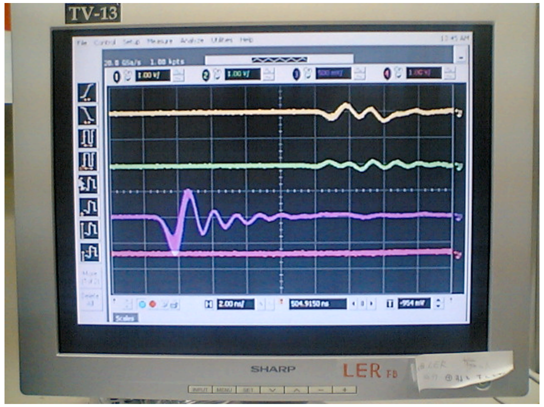
1. α_p=-2.5x10^{-4},

   pilot bunch (1 mA)

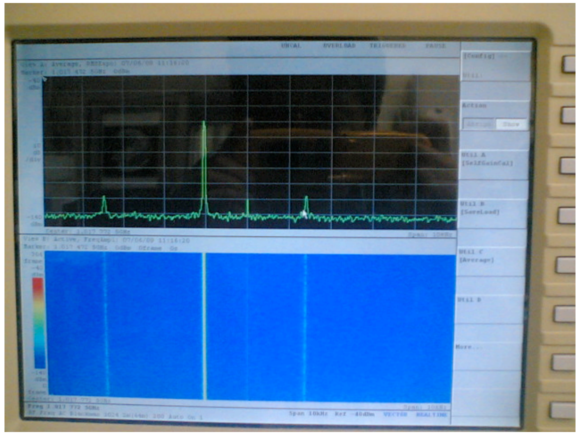


2. α_p=-3.4x10^{-4}

   pilot bunch (1 mA)



multibunch(99) 5 mA



~2.5kHz

High Emittance Optics

- Motivation
  - To increase the bunch current particularly in HER
    - To compare the specific luminosity with a higher bunch current product
    - Preparation of the higher beam operation with crab cavities
- Results
  - HER: high emittance optics (ε_x= 34nm)
  - LER: ε_x= 24$\rightarrow$ 18nm
  - We could store somewhat high HER beam current. But it was not enough.

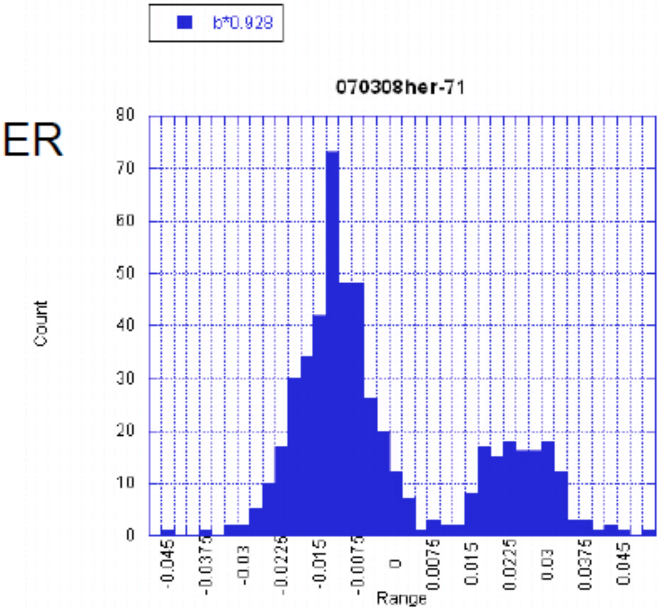
HER crab angle is small?

- Observed HER tilt by crab kick is half of the calculation.
- Closed orbit distortion by crab kick is consistent with the calculation.
- IP horizontal orbit offset created by crab kick is consistent with the calculation.
- Is there any mechanism which affects x-z particle distribution?

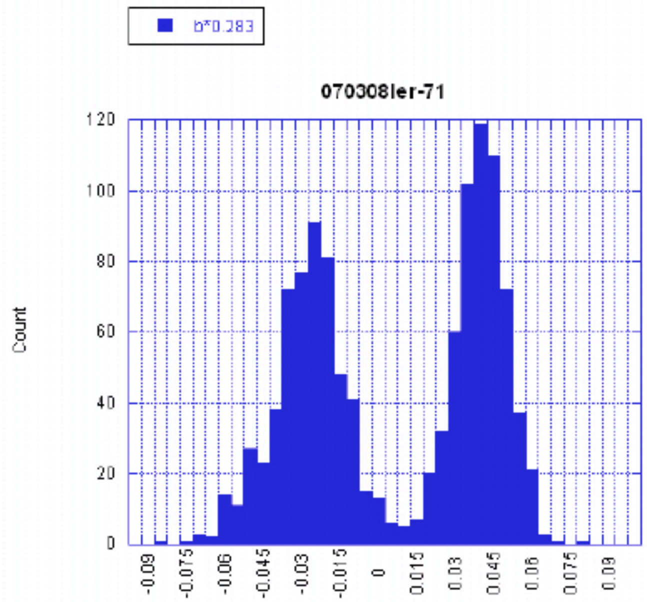
Measurement : tilt

- The results of the tilt calculations are shown below.
- The two peaks correspond to the two sweep phase of the streak camera.
- LER values are consistent with the expected value, but HER values are off by a factor of 2.

HER

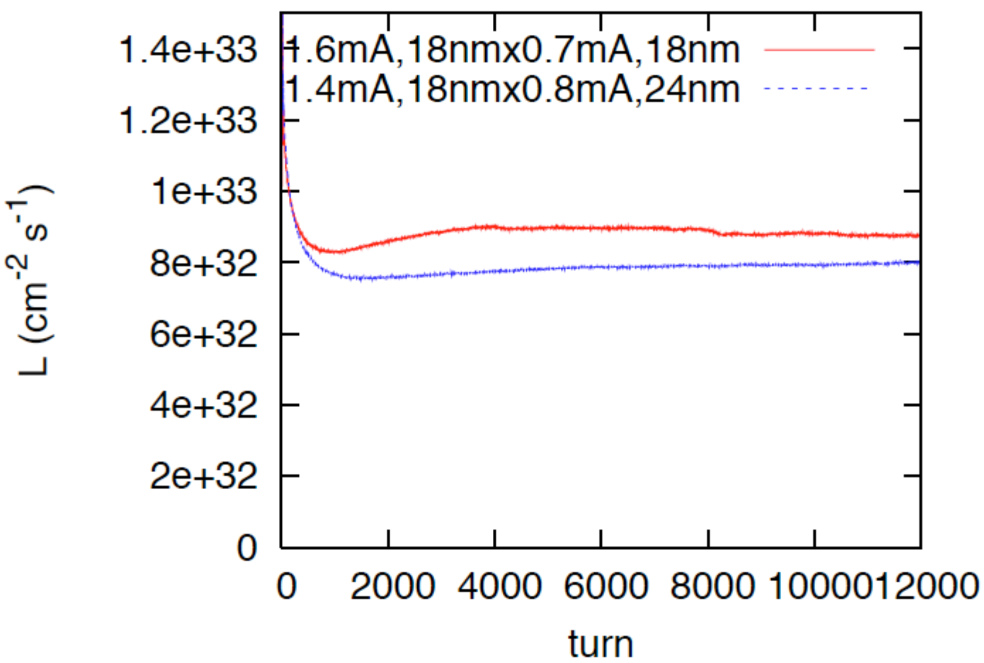


LER

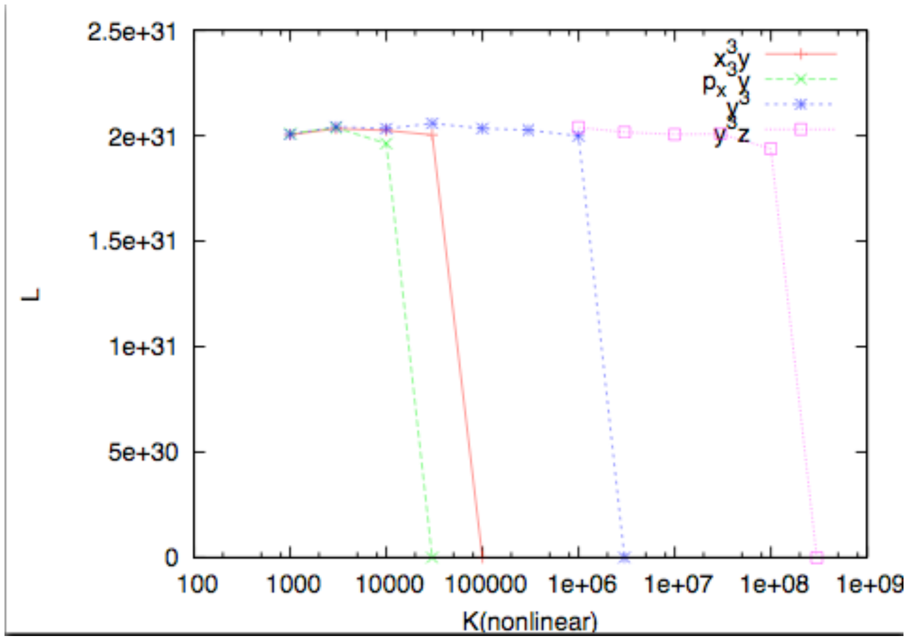


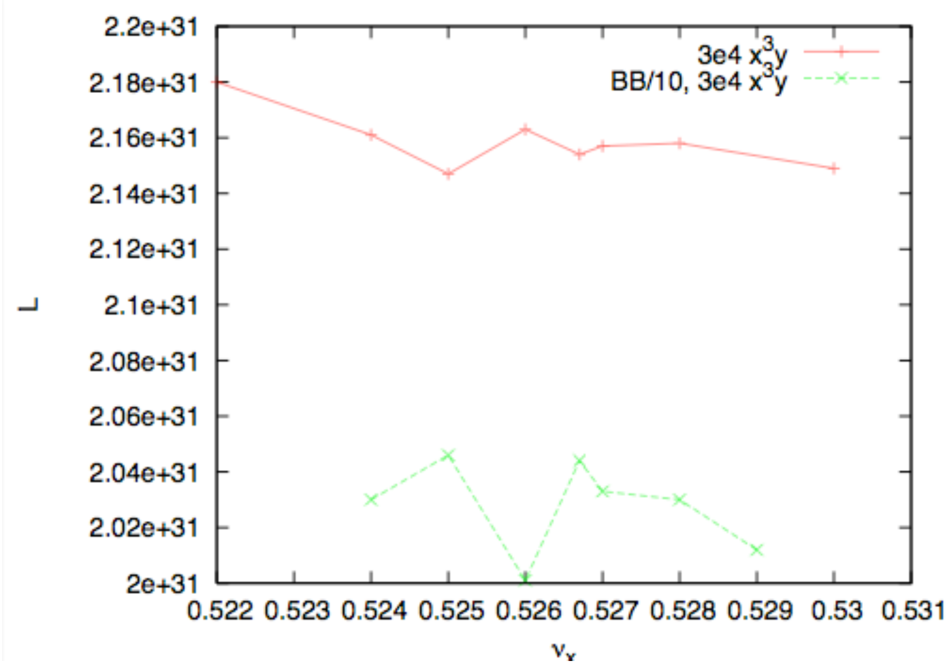
Unbalance of horizontal emittance (Ohmi)

- Unbalance of horizontal emittance between two beams can be compensated by beam currents.



Beam-Beam Simulation with lattice non-linearity (Ohmi)





- Luminosity drops abruptly at some threshold strengths.
- However, the threshold strengths are about 2 order higher than expected values.

Definition of R matrix

- Definition in the SAD code

$$\begin{pmatrix} u \\ p_u \\ v \\ p_v \end{pmatrix} = T \begin{pmatrix} x \\ p_x \\ y \\ p_y \end{pmatrix}$$

Normal (uncoupled) coordinate — Usual coordinate

$$T(s) = \begin{pmatrix} \mu I & SR^t S \\ R & \mu I \end{pmatrix} = \begin{pmatrix} \mu & 0 & -R4 & R2 \\ 0 & \mu & R3 & -R1 \\ R1 & R2 & \mu & 0 \\ R3 & R4 & 0 & \mu \end{pmatrix}$$

R matrix

$$S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

$$\mu^2 + \det R = 1$$