Performance of KEKB with Crab Cavities

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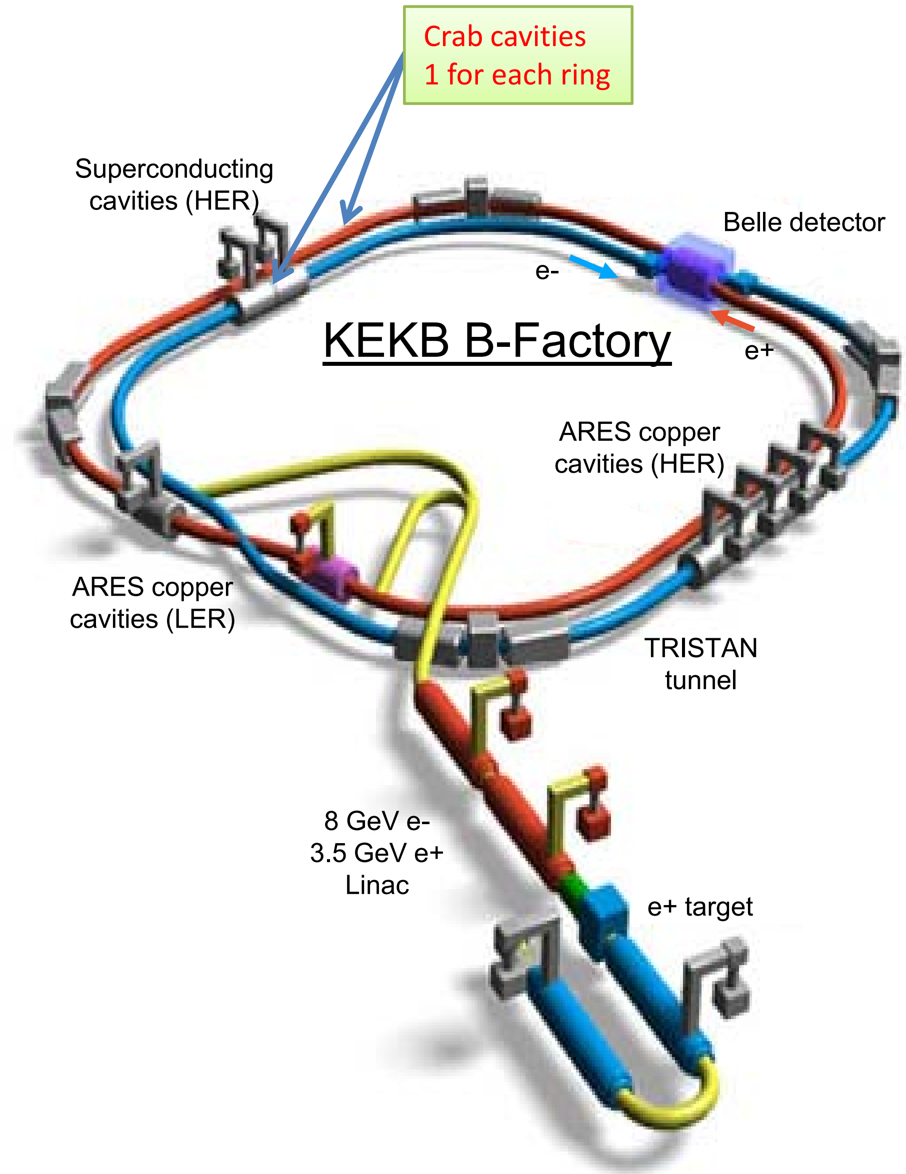
KEK

Outline

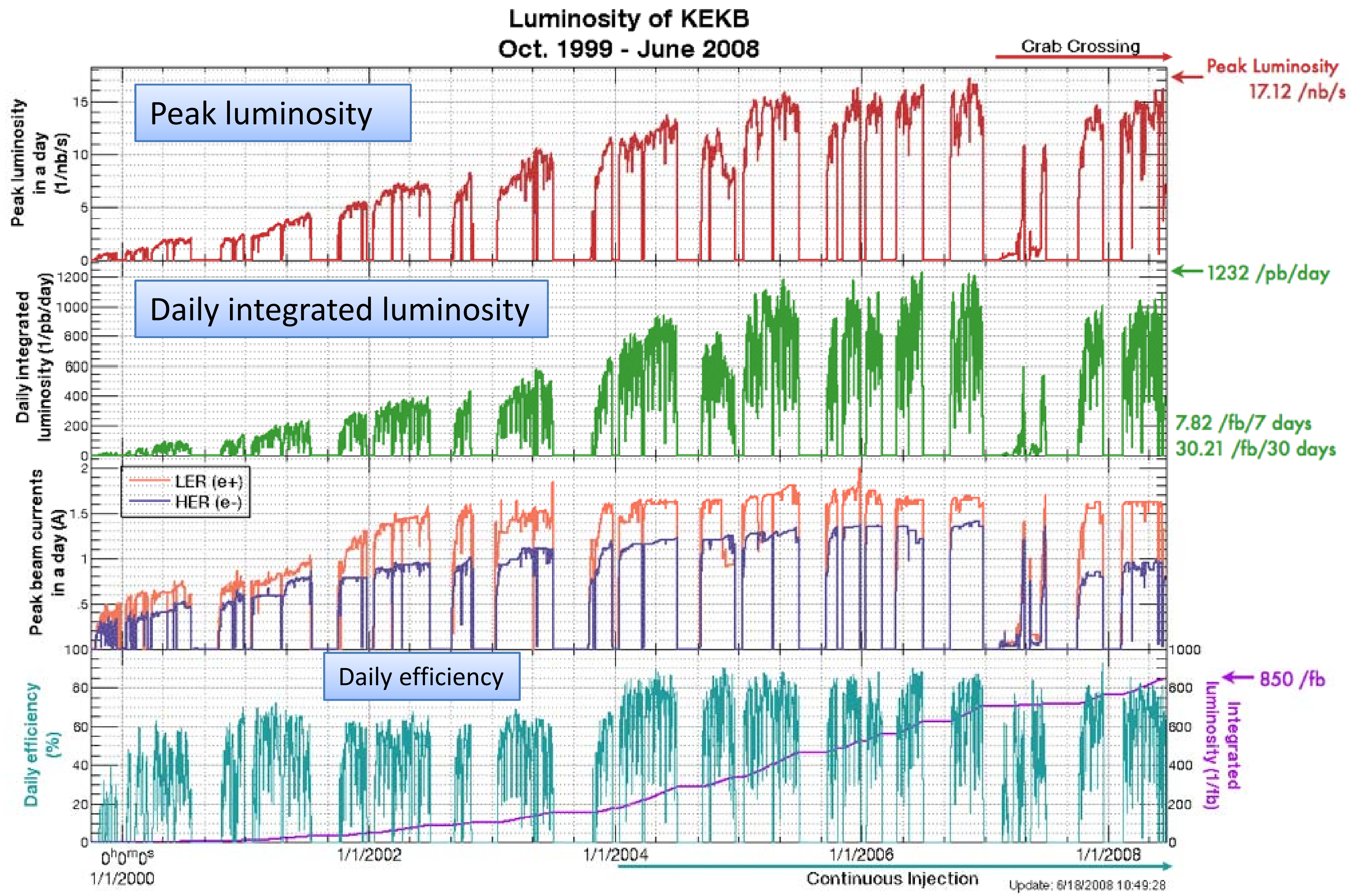
- Overview of KEKB
- Crab cavity and crab crossing scheme
- Performance of KEKB with crab crossing
- Some experience of crab cavity operation with beams
- Summary and future plans

Overview of KEKB

- Circumference:
  - 3016m
- Beam energy
  - 3.5 GeV (e+; LER)
  - 8.0 GeV (e-; HER)
  - E_{cm} = 10.58GeV (∏(4S))
- Beam Currents*
  - 1.8A [1.62A] (2.6A) (LER)
  - 1.34A [0.95A] (1.1A) (HER)
- Number of Bunches: 1585/ring (~5000)
- Horizontal crossing Angle:
  - 22mrad or crab crossing
- Peak Luminosity
  - $1.0 \times 10^{34} cm^{-2}s^{-1}$ on May 09 2003
  - $1.71 \times 10^{34} cm^{-2}s^{-1}$ (record w/o crab)
  - $1.61 \times 10^{34} cm^{-2}s^{-1}$ (record w/ crab)
- Physics:
  - B physics (Asymmetric) (Belle)
- Integrated Luminosity:
  - Total:>850 fb^{-1}
  - ~ 1fb^{-1}/day (record: 1.23 fb^{-1}/day)



*Beam currents: [ ]: w/ crab, ( ):design



Luminosity of KEKB
Oct. 1999 - June 2008
Crab Crossing
Peak Luminosity
17.12 /nb/s
Peak luminosity
Peak luminosity in a day (1/nb/s)
Daily integrated luminosity
Daily integrated luminosity (1/pb/day)
1232 /pb/day
7.82 /fb/7 days
30.21 /fb/30 days
LER (e+)
HER (e-)
Peak beam currents in a day (A)
Daily efficiency
Daily efficiency (%)
850 /fb
Integrated luminosity (1/fb)
0h0m0s
1/1/2000
1/1/2002
1/1/2004
1/1/2006
1/1/2008
Continuous Injection
Update: 6/18/2008 10:49:28

Crab cavity and crab crossing scheme

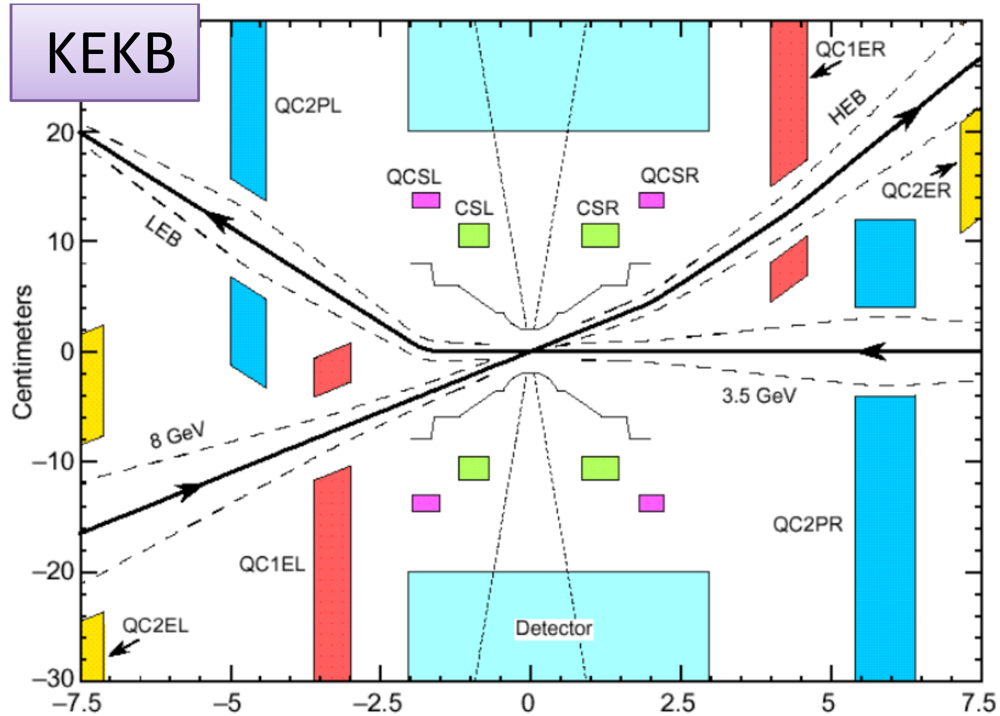
Crabcrossing scheme: some history

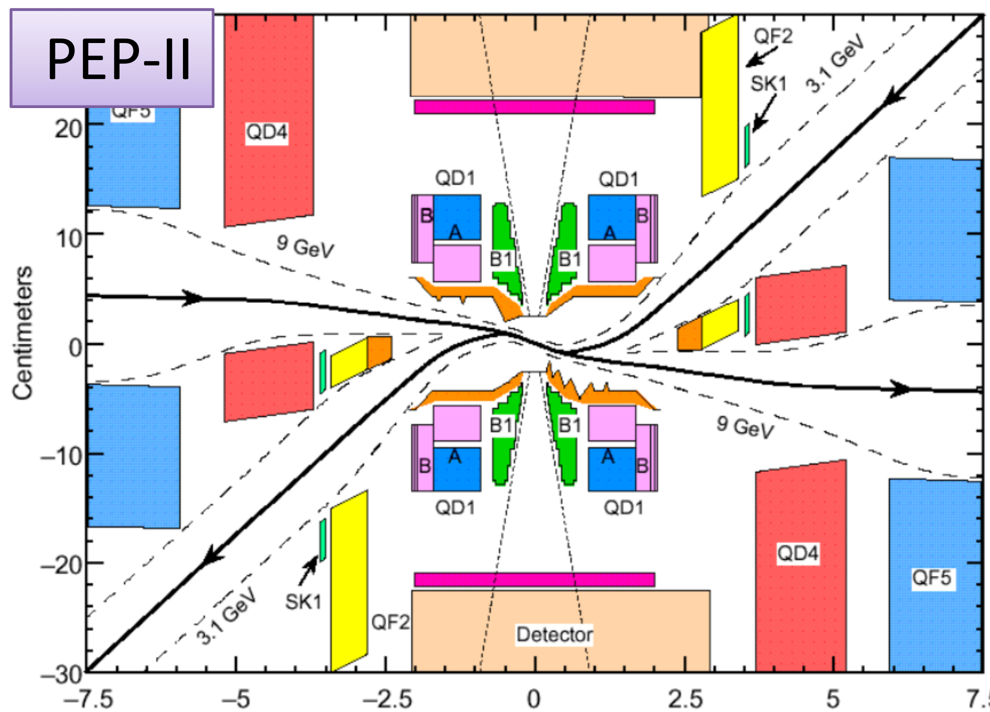
- The crab crossing scheme was proposed in 1988 by R. Palmer.
  - Idea to recover the head-on collision with the crossing angle for linear colliders.
- Also in ring colliders
  - Oide and Yokoya showed that the synchro-betatron coupling terms associated with the crossing angle are canceled by the crab crossing (1989).
- KEKB adopted a horizontal crossing angle of 22mrad.
- The crab cavities were considered as backup devices in KEKB design.
- The KEKB crab cavity was first designed by K. Akai at Cornel (1991-1992)
- R&D of crab cavity started at KEKB in 1994.

K. Hosoyama: Development of the KEK-B Superconducting Crab Cavity
Thursday26 Morning Session in the Maestrale Auditorium

Horizontal crossing angle

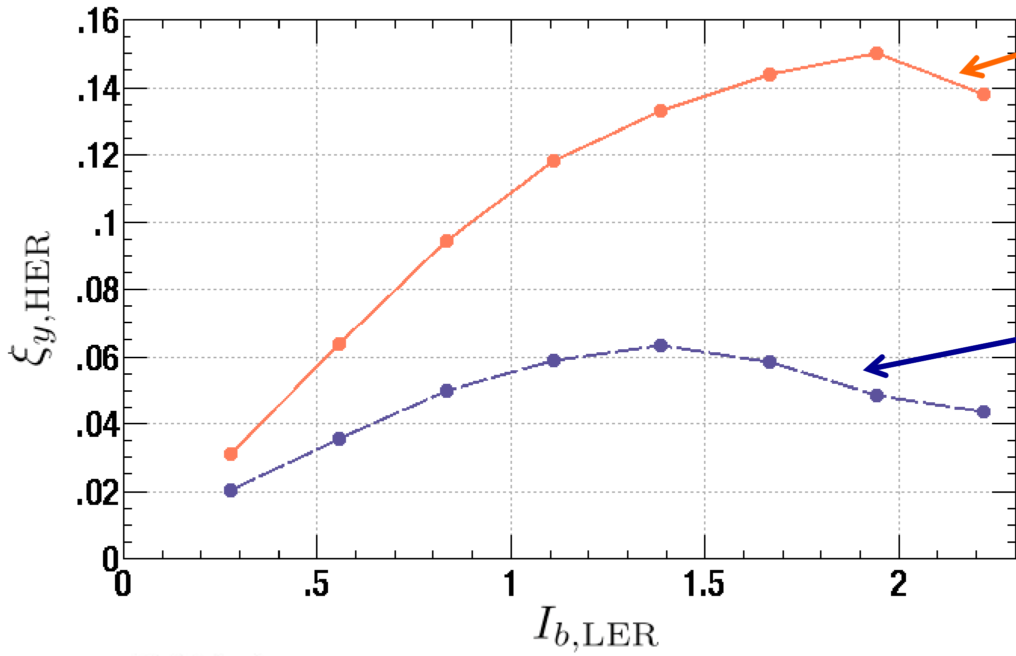
- KEKB adopted 22mrad horizontal crossing angle.
  - Easier beam separation
  - Less SR background
  - Less Luminosity-dependent background
  - Space for solenoid compensation
  - Less parasitic collision
- Possible demerit
  - Synchro-betatron resonance ->We continued development of crab cavity as a backup device.
- Observation
  - No serious effects of s-b resonance
  - We got ξ_y of 0.056 w/o crab cavity.





Crab crossing at KEKB

- Crab Crossing can boost the beam-beam parameter higher than 0.15 ! (K. Ohmi)

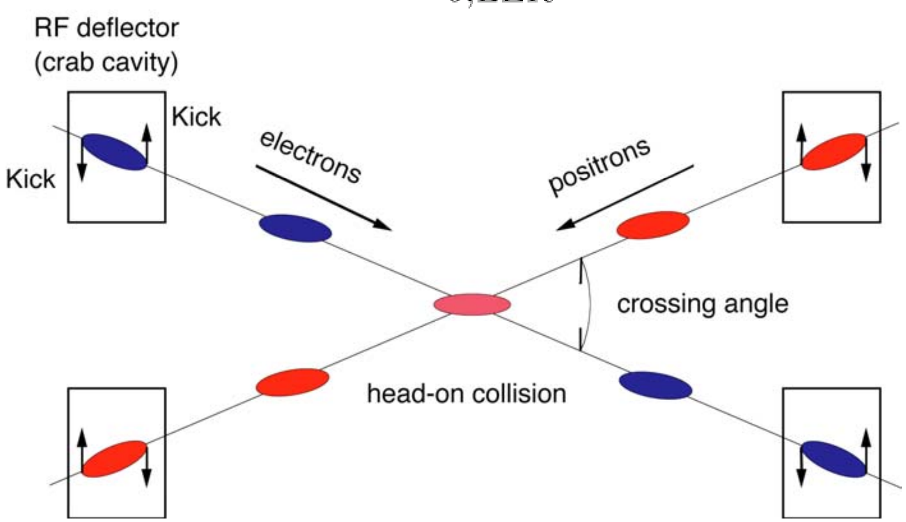


Head-on (crab)

Strong-strong beam-beam simulation

22mrad crossing angle

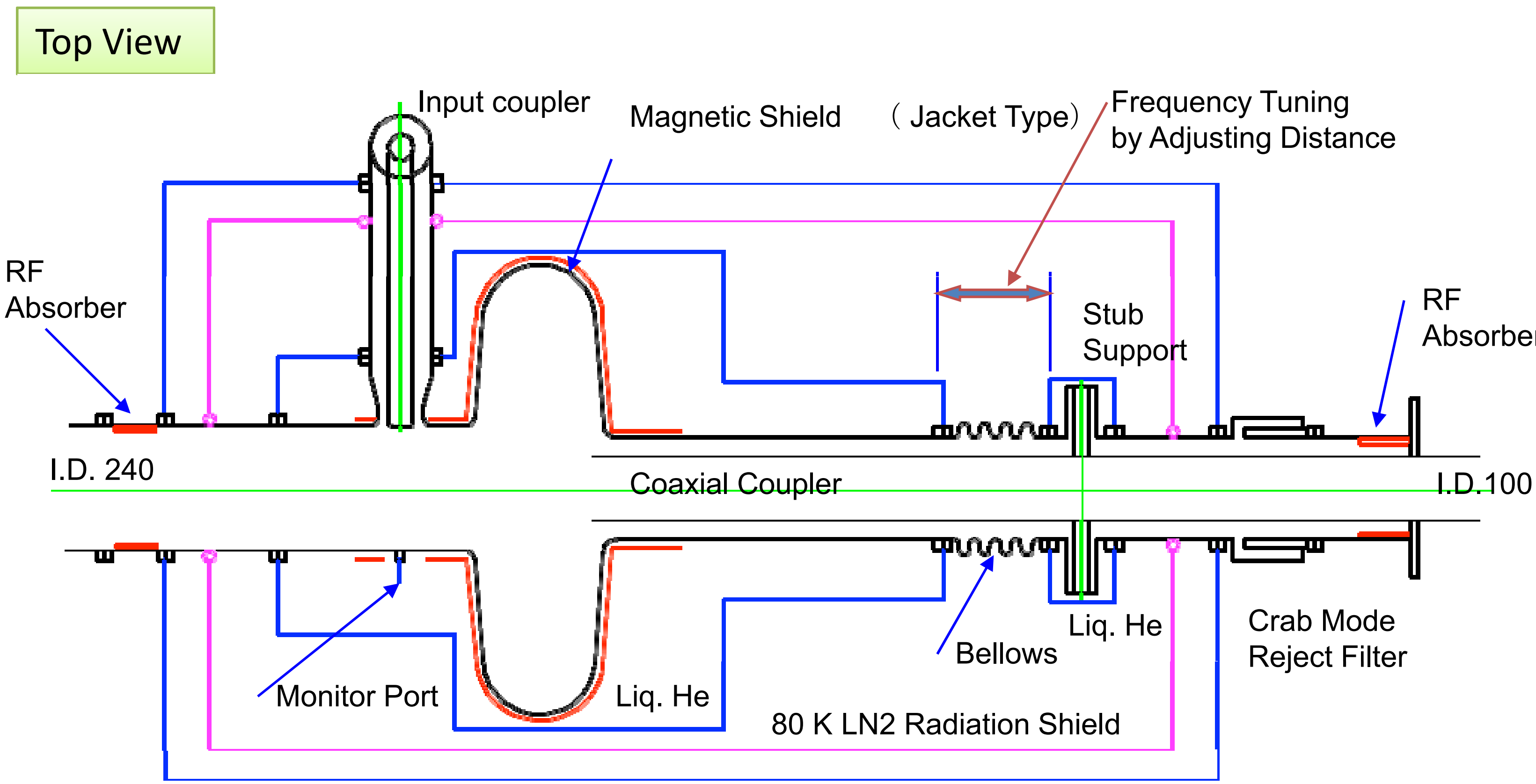
Head-on
ν_x=.508 } → ξ_y~0.15



First proposed by R. B. Palmer in 1988 for linear colliders.

- After this simulation appeared, the development of crab cavities was revitalized.

Structure of crab cavity



crab mode: TM110: B_y on beam axis
lower mode: TM010: dumped through coaxial coupler

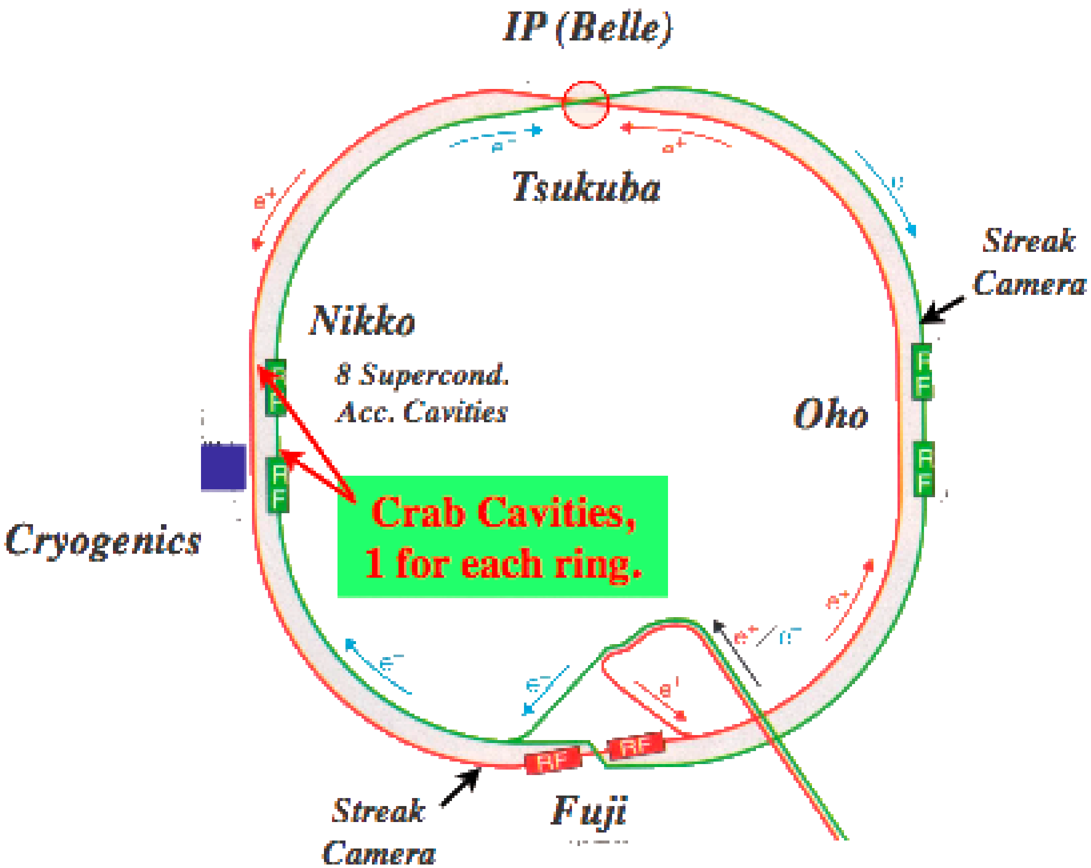
Finally two crab cavities were installed in KEKB, one for each ring in February 2007!

HER (e-, 8 GeV)

LER (e+, 3.5 GeV)

…..after 13 years' R&D from 1994

Single crab cavity scheme



•Beam tilts all around the ring.
•z-dependent horizontal closed orbit.
•tilt at the IP:

$$\frac{\theta_x}{2} = \frac{\sqrt{\beta_x^C \beta_x^*}\cos(\psi_x^C - \mu_x/2)}{2\sin(\mu_x/2)} \frac{V_C \omega_{\rm rf}}{Ec}$$

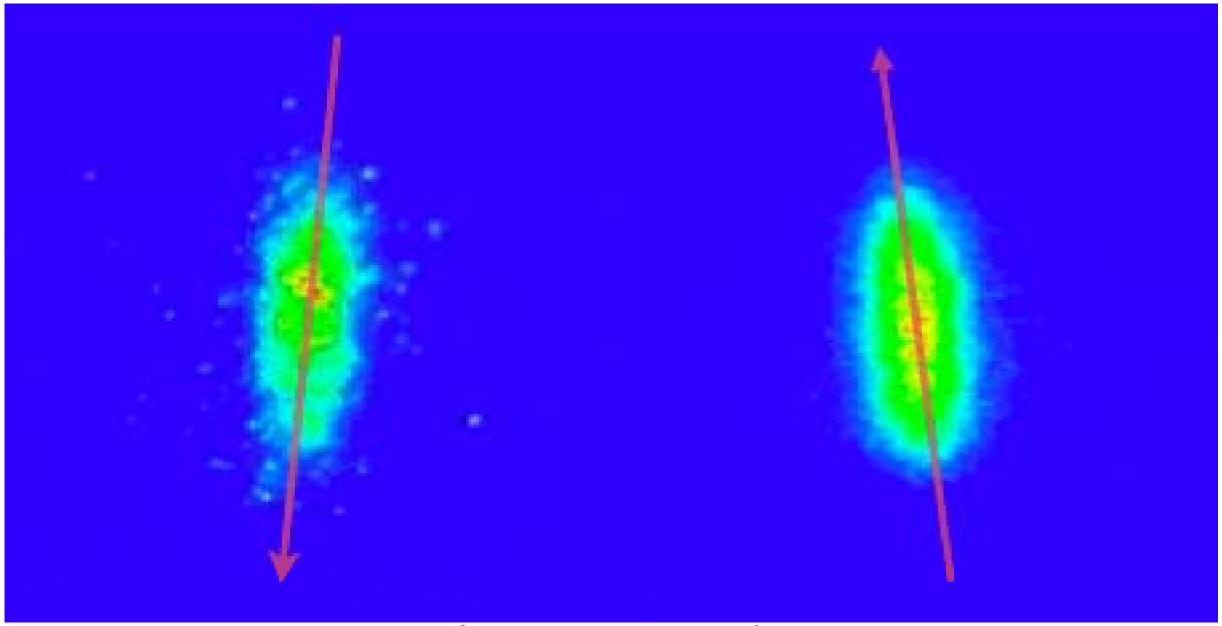
	LER	HER	
ϕ_{cross}	22		mrad
β_x^*	$80 \sim 90$	$80 \sim 90$	cm
β_x^C	68	130	m
ν_x	45.506	44.511	
$\psi_x^C/2\pi$	0.25	0.25	
V_C	0.83	1.37	MV
f_{RF}	508.89		MHz

❖ 1 crab cavity per ring.
❖ saves the cost of the cavity and cryogenics.
❖ avoids synchrotron radiation hitting the cavity.

Beam was indeed tilted!

Observation with Streak Cameras (H. Ikeda et al)

inside of the rings



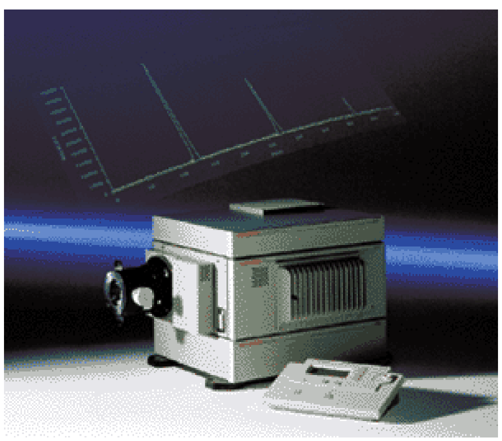
outside of the rings

longitudinal

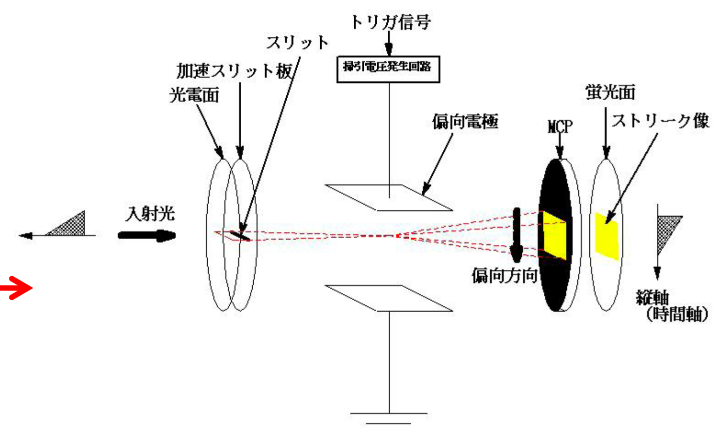
horizontal

LER

HER

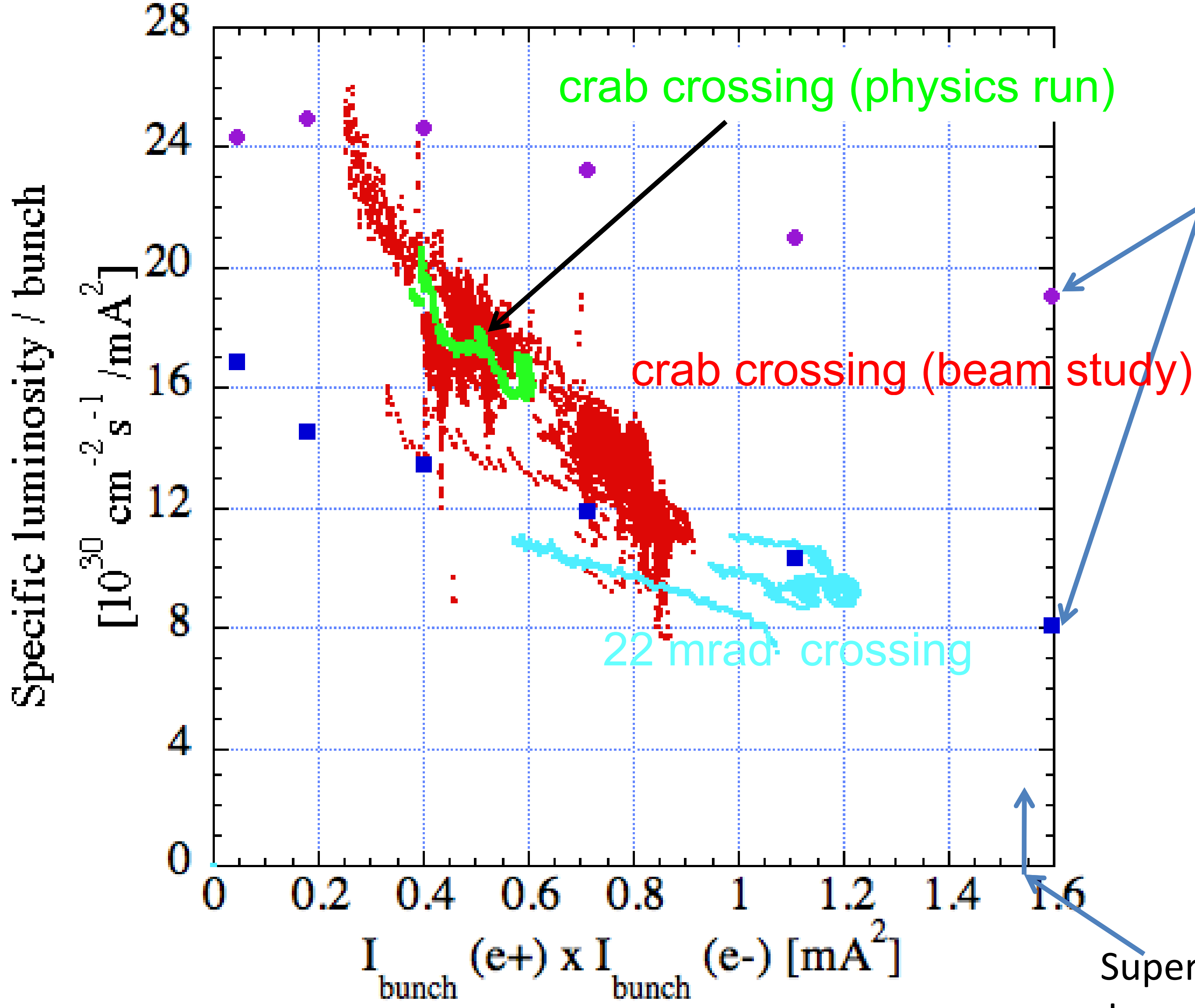


The streak camera



Performance of KEKB with crab crossing

Specific luminosity with crab crossing



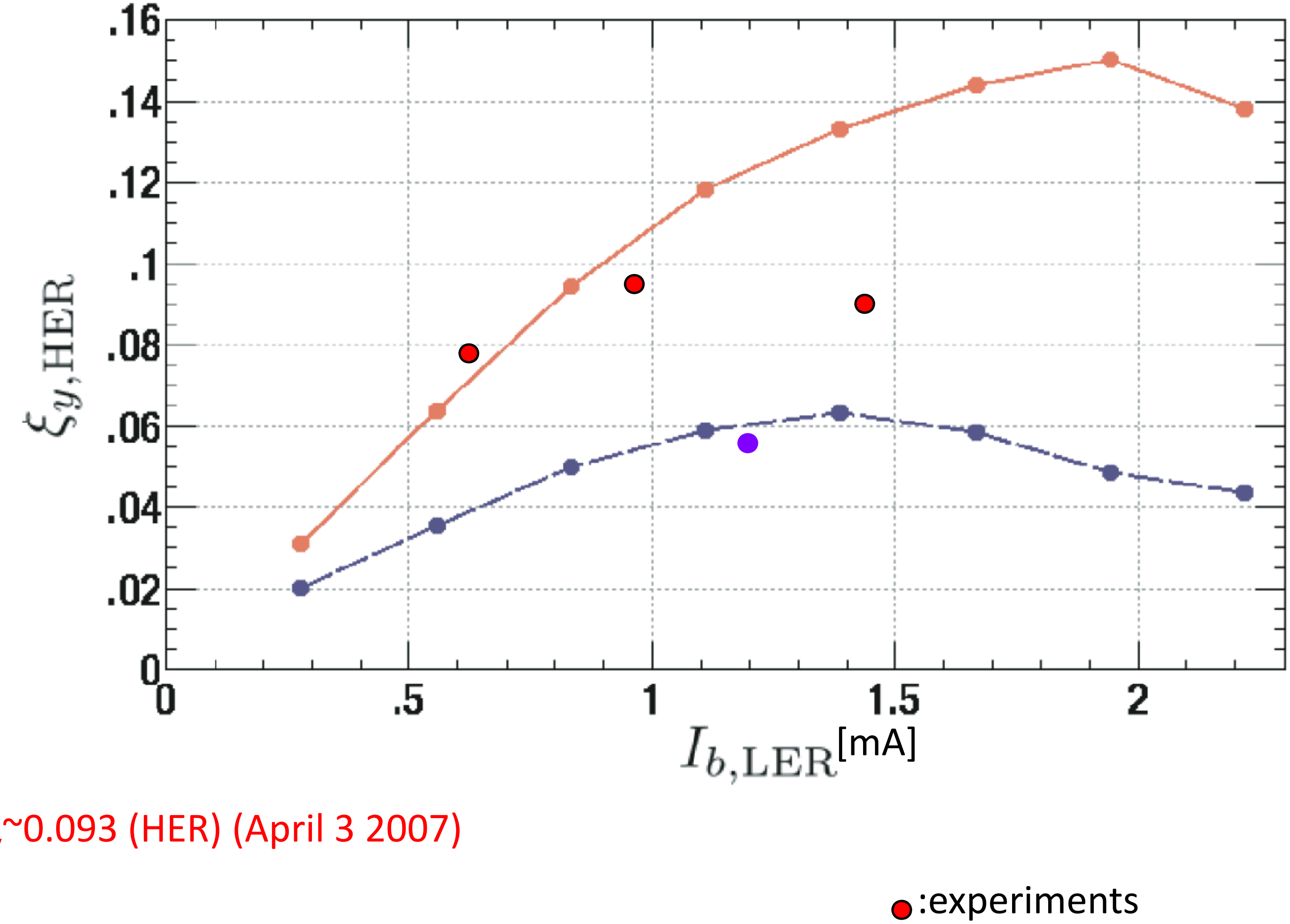
Beam-beam simulation (strong-strong)

SuperKEKB (1.53mA²)
I_{bunch} (LER) = 1.87 mA
I_{bunch} (HER) = 0.82 mA

Machine parameters

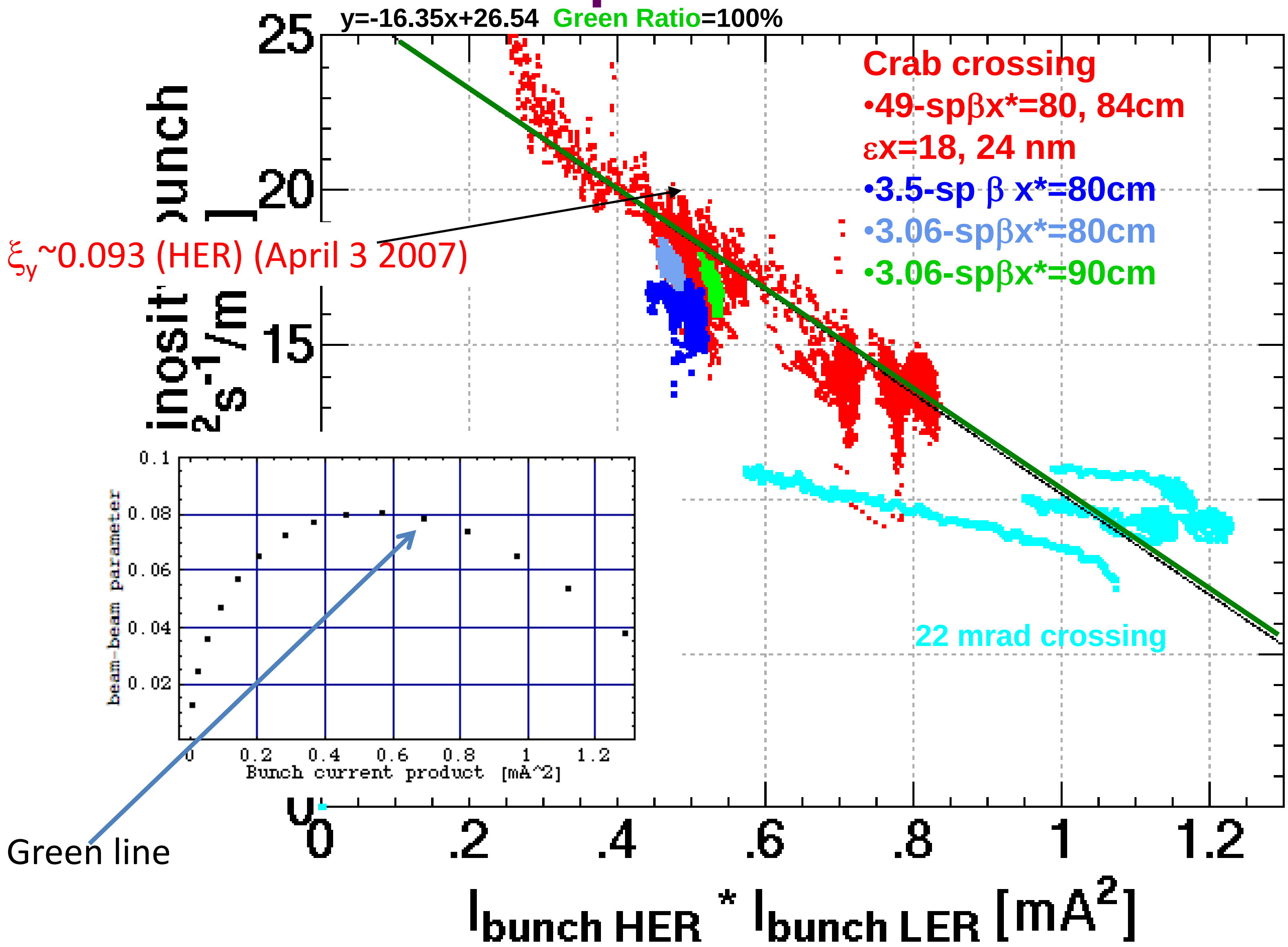
	Nov. 2006 (w/o crab)		Mar. 2008 (with crab)		Units
	LER	HER	LER	HER	
Circumference	3016				m
Hor. emittance	18	24	15	24	nm
Beam current	1662	1340	1605	934	mA
# of bunches	1388+1		1584 + 1		
RF frequency	508.88				MHz
RF Voltage	8.0	15.0	8.0	13.0	MV
ν_s	-0.0246	-0.0226	-0.0240	-0.0204	
ν_x / ν_y	45.505/43.534	44.509/41.565	45.505/43.567	44.509/41.596	
β_x^* / β_y^*	59/0.65	56/0.59	90/0.59	90/0.59	cm
⟨ (mom. compact.)	3.31×10^{-4}	3.38×10^{-4}	3.17×10^{-4}	3.38×10^{-4}	
ξ_x / ξ_y	0.117/0.105	0.070/0.056	0.099/0.097	0.119/0.092	
Beam life	110@1600	180@1340	94@1605	158@934	min.@mA
Luminosity	1.712		1.610		$10^{34} cm^{-2} s^{-1}$

Beam-beam parameter



ξ_y~0.093 (HER) (April 3 2007)

Specific Luminosity and beam-beam parameter



Why the specific luminosity drops faster than expected?

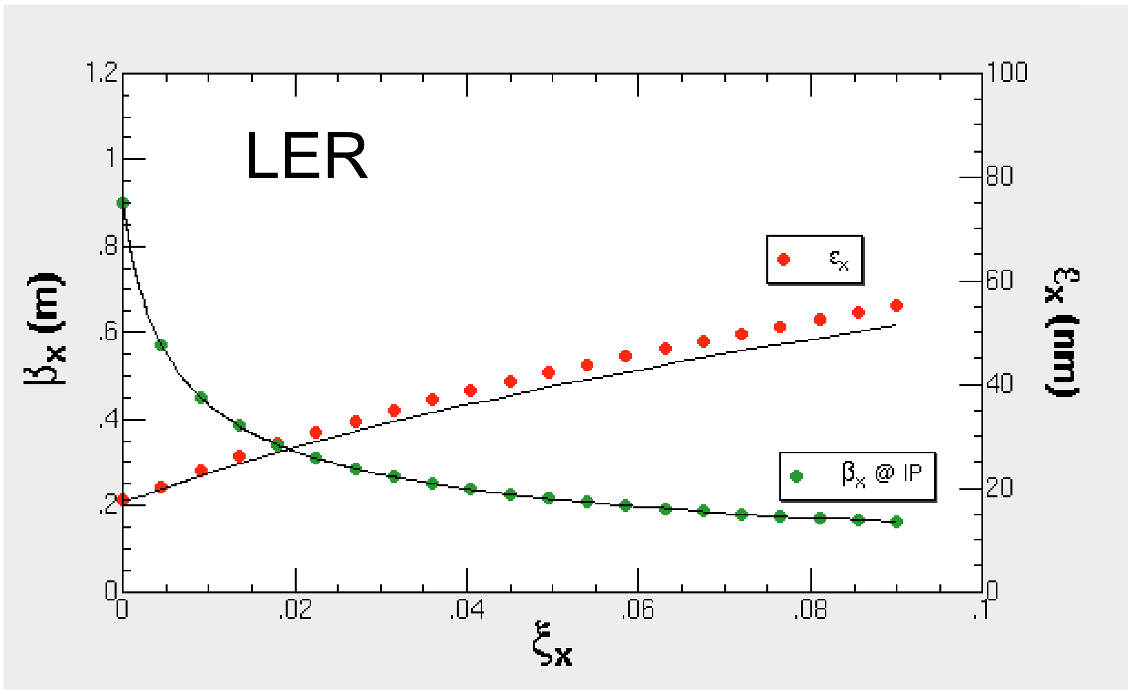
- Speculations:
  - ✧Too many tuning parameters to find out an optimum set?
  - ✧Short beam lifetime prevents us from approaching a better parameter set?
    - ✧Dynamic-β and dynamic emittance effects due to beam-beam?
    - ✧Beam lifetime decrease dependent on horizontal orbit offset at IP
  - ✧Synchro-betatron resonance near 1/2 integer?
  - ✧Some unknown fast noise?
  - ✧Crosstalk between beam-beam and lattice non-linearity?
  - ✧Vertical crab at IP?
  - ✧and more….

Too many tuning parameters?

Knob	Observable	frequency: every
Relative beam offset IP	Beam-beam kick measured by BPMs around the IP	1 sec
Relative beam angle IP	BPMs around the IP	1 sec
Global closed orbit	All $\sim$ 450 BPMs	15 sec
Beam offset at crab cavities[11]	BPMs around the crab cavity	1 sec
Betatron tunes	tunes of non-colliding pilot bunches	$\sim$ 20 sec
Relative rf phase	center of gravity of the vertex	10 min.
Global couplig, dispersion, beta-beat	orbit response to kicks & rf frequency	$\sim$ 14 days
LER to HER crab voltage ratio	response in the hor. beam-beam kick. vs. crab rf phase	$\sim$ 7 days
Rf phase of crab cavity	hor. kick vs. crab voltage response	$\sim$ 7 days
Vertical waist position	$\mathcal{L}$ and σ_y at the SRM	$\sim$1 day
Local x-y couplings and dispersions at IP	$\mathcal{L}$ and σ_y at the SRM	$\sim$1 day each
Sextupole settings	$\mathcal{L}$ and lifetime	$\sim$ 3 days
X-y coupling parameter at the crab cavities	$\mathcal{L}$ and σ_y at the SRM	$\sim$ 3 days
Crab kick voltage	$\mathcal{L}$ and σ_y at the SRM	$\sim$ 7 days

- Many tuning knobs are tuned by scans only on the luminosity and the beam sizes and the beam lifetime.
- Each scan takes a long time, typically ~30min.
- During beam operation, the operators are almost always doing some scan.
- Is it possible to reach an optimum set of parameters with this method?
- We still suspect this possibility.

Dynamic-β and dynamic emittance by beam-beam (calculation)

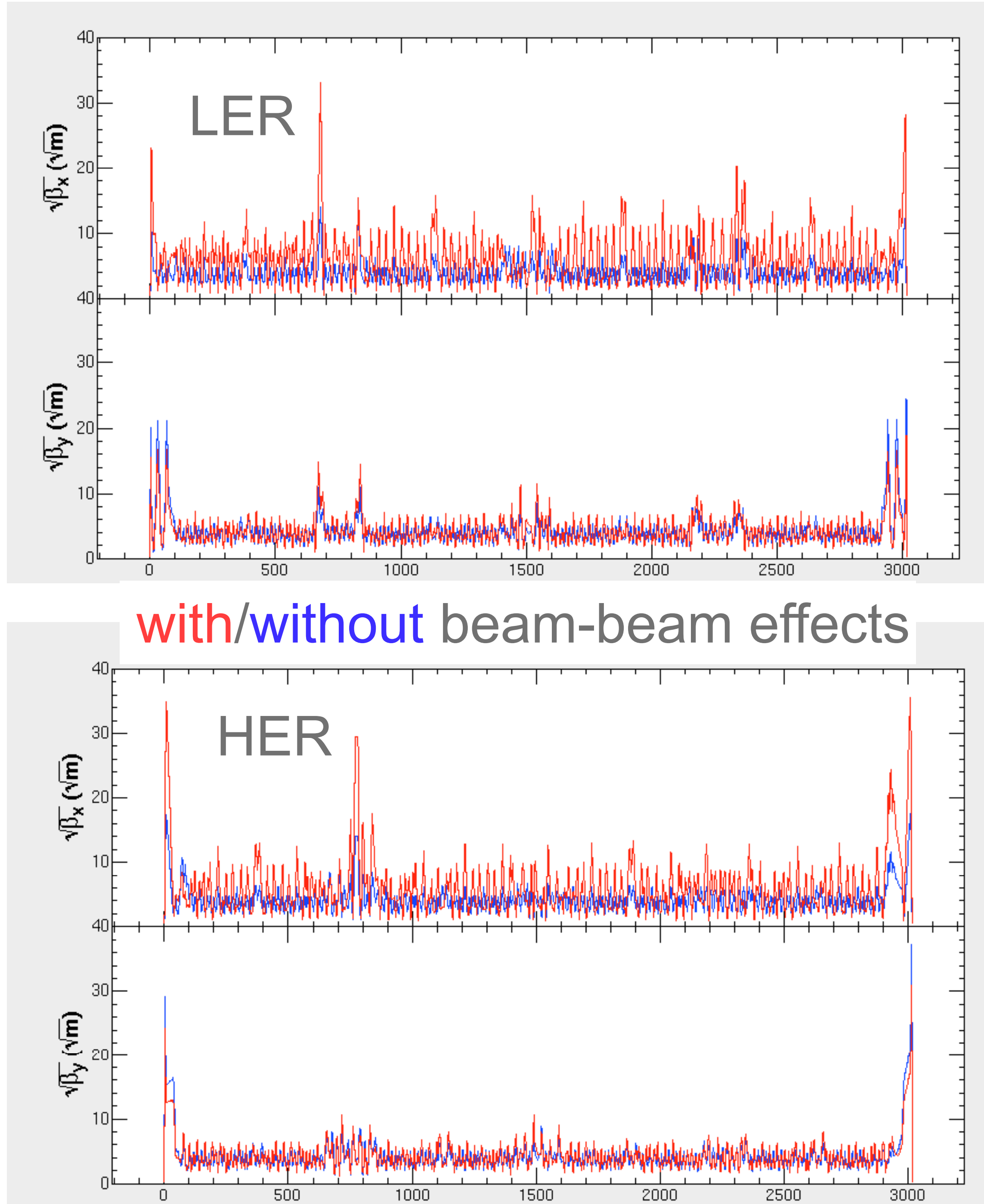


LER

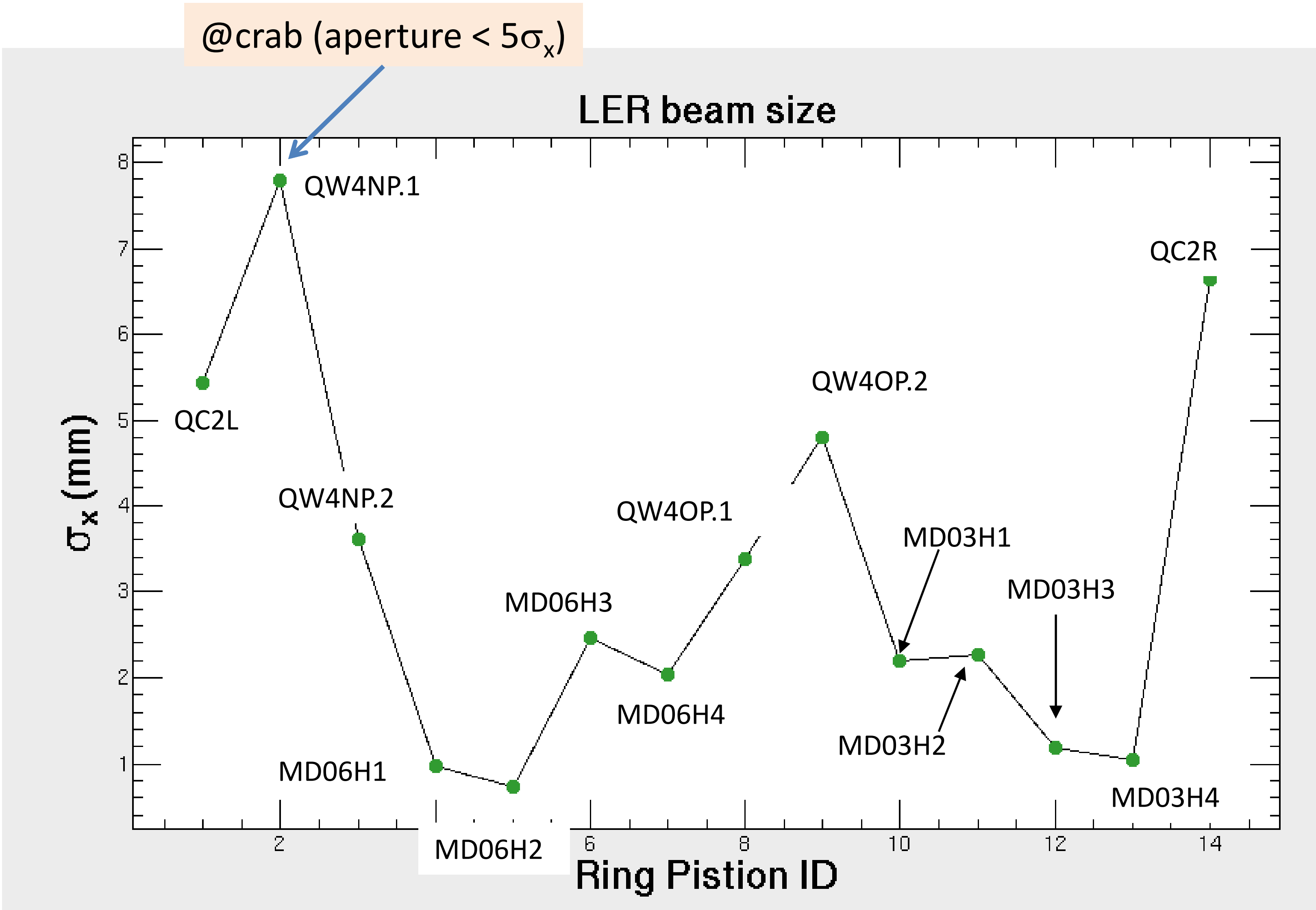
ν_x	45.506
ν_y	43.57
β_x [m]	.9
β_y [m]	.0059
ξ_x max	.09
ξ_y max	.1

The focusing force of the beam-beam interaction not only squeezes the beam at the interaction point, but increases the emittance drastically.

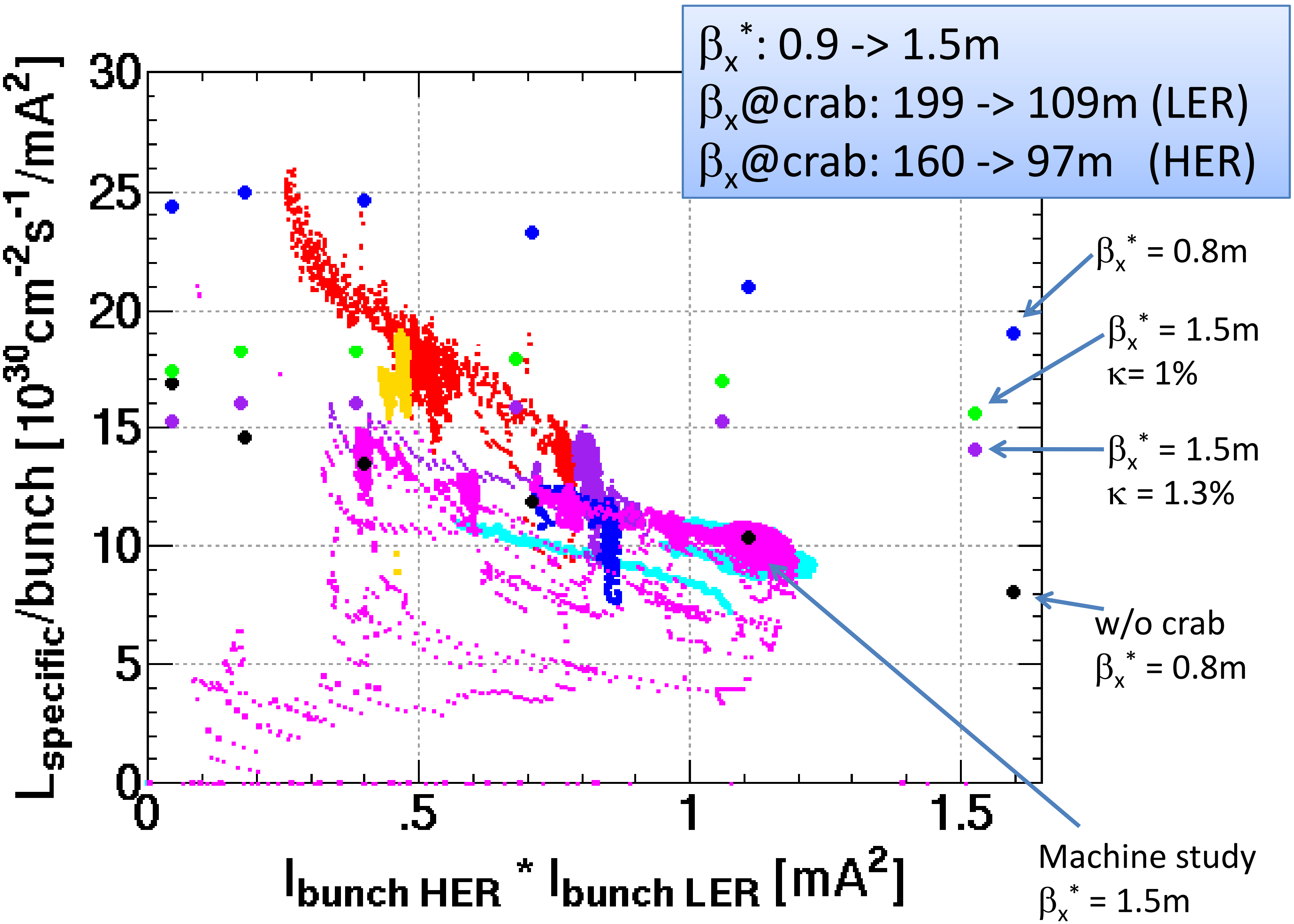
Deformation of β-function all around the ring due to beam-beam effect ("dynamic beta")



Beam size calculation with dynamic beam-beam effects

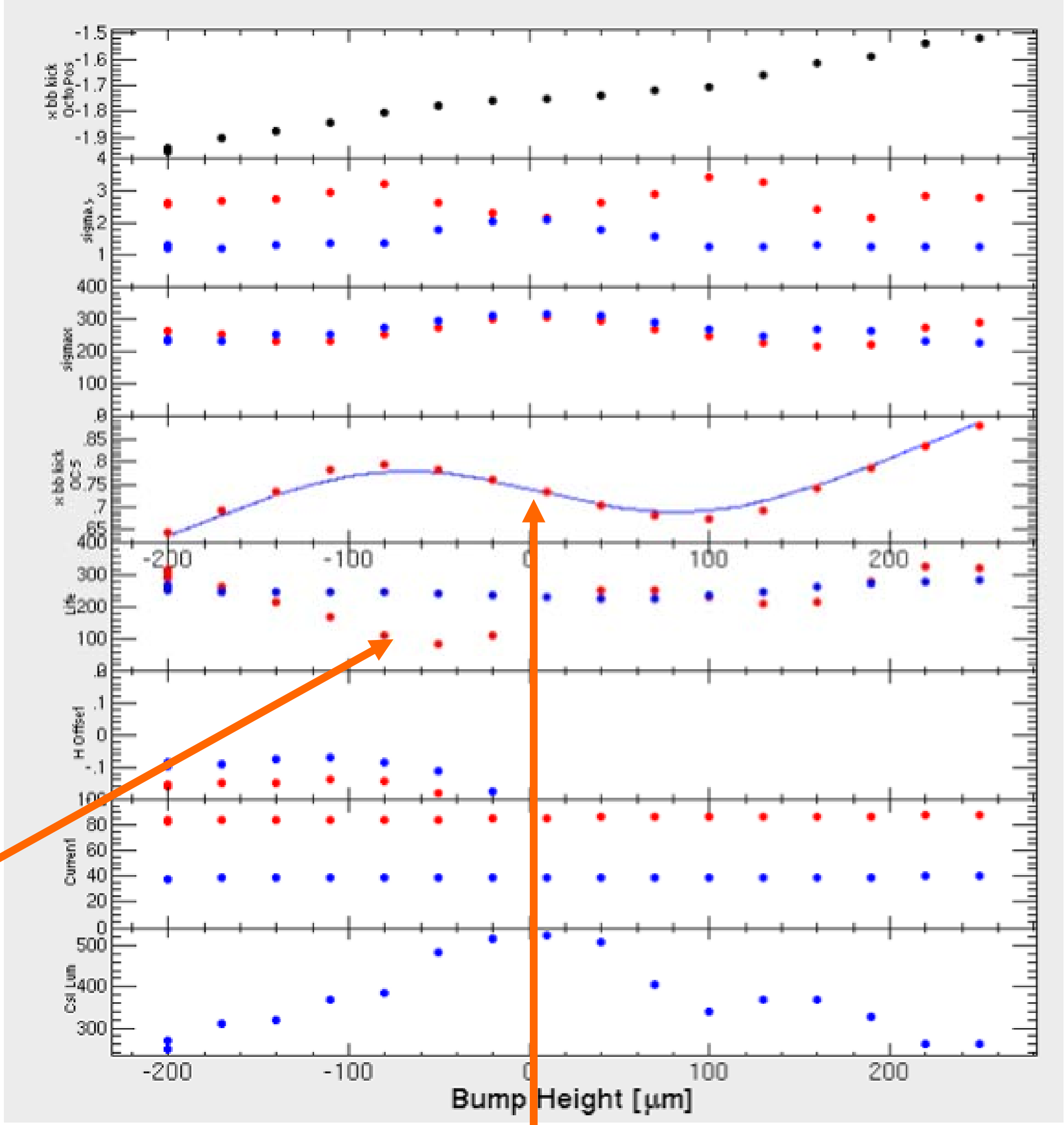


Trial of higher β_x^*



Mysterious lifetime asymmetry with respect to sign of hor. offset

- 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.

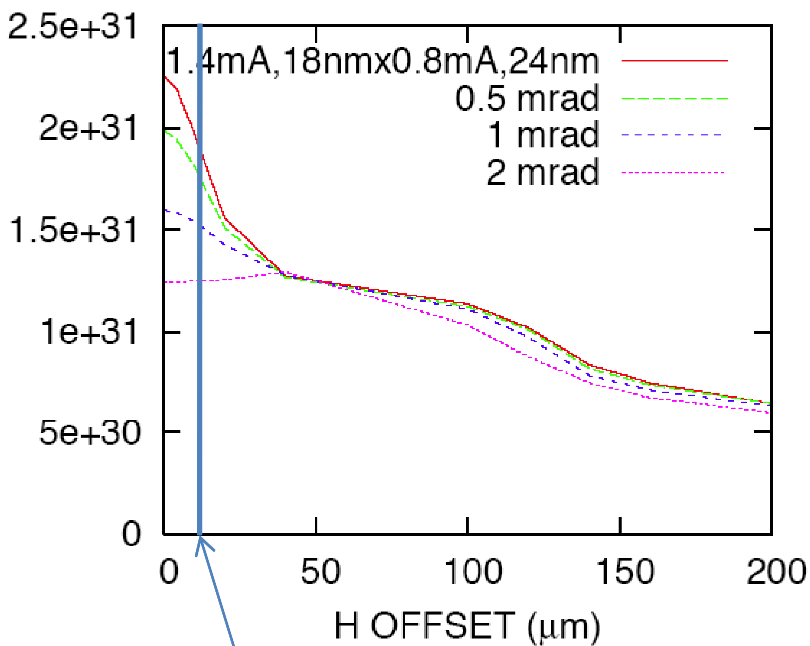


LER lifetime

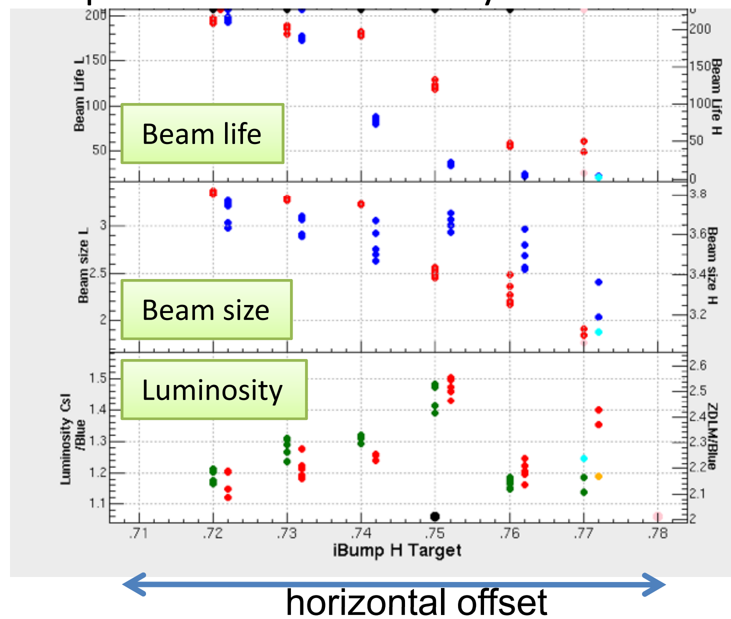
Collision center given by the beam-beam kick

Horizontal offset at IP and crossing angle

Beam-beam simulation

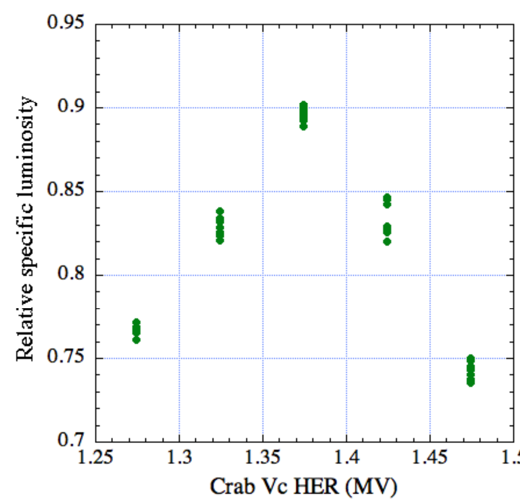


Horizontal offset scan:
experiment with relatively small beam current

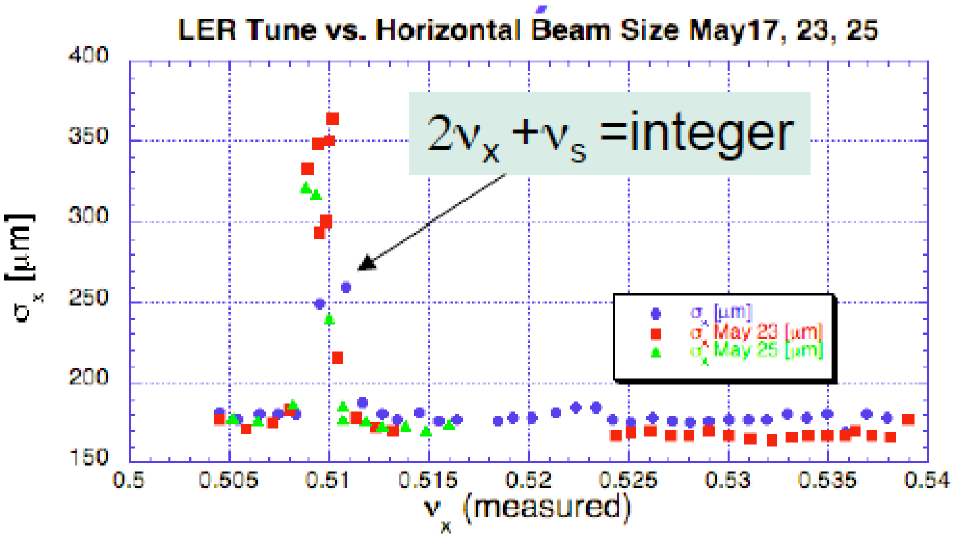


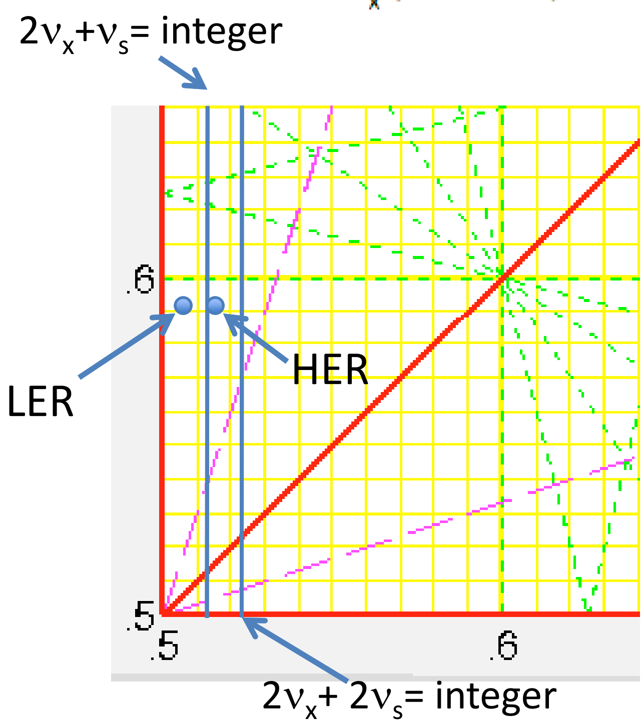
- Luminosity boost by crab crossing disappears with 2 mrad crossing angle.
- Luminosity boost by crab crossing disappears with ~40μmhorizontal offset.
- Typical value of horizontal offset in physics experiment is ~15μm, which is obtained by offset scan.
- This kind ofhorizontal offset depending on beam currentcan degrade the specific luminosity.
- Some luminosity boost by the crab crossing is actually observed by crab Vc scan.

Crab Vc scan (experiment in physics run)



Synchro-betatron resonance





- The horizontal tune is set nearby the half integer resonance and its synchrotron side bands.
- On the resonances, some harmful effects are observed.
  - Single-beam beam size blowup
  - Tow-beam beam size blowup
  - Beam lifetime reduction (or beam loss)
- The resonance is stronger in HER where no local chromaticity correction is installed.
- Strength of the resonance is strongly dependent on a choice of sextupole setting. The luminosity also changes by changing the sextupole setting.
- Even in the off resonance tunes, it affects the luminosity due to the tune footprint by the beam-beam?
- We still suspect this resonance.

Negative-αOptics

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

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

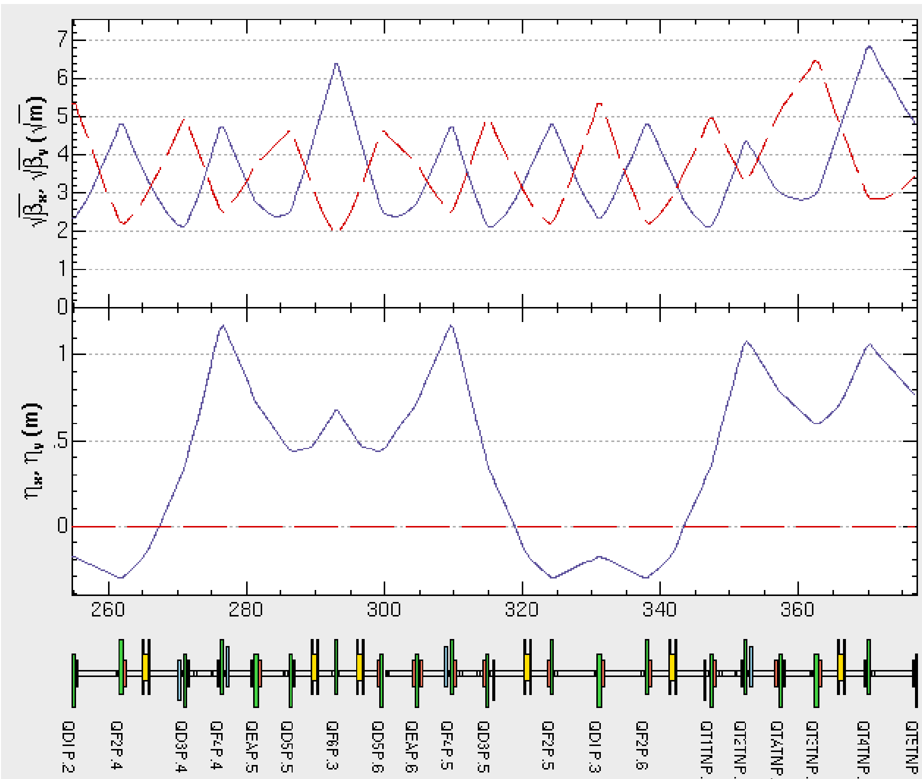
$2\nu_x + 2\nu_s$ = integer → $2\nu_x - 2\nu_s$ = integer

ν_x: .5112, .5224

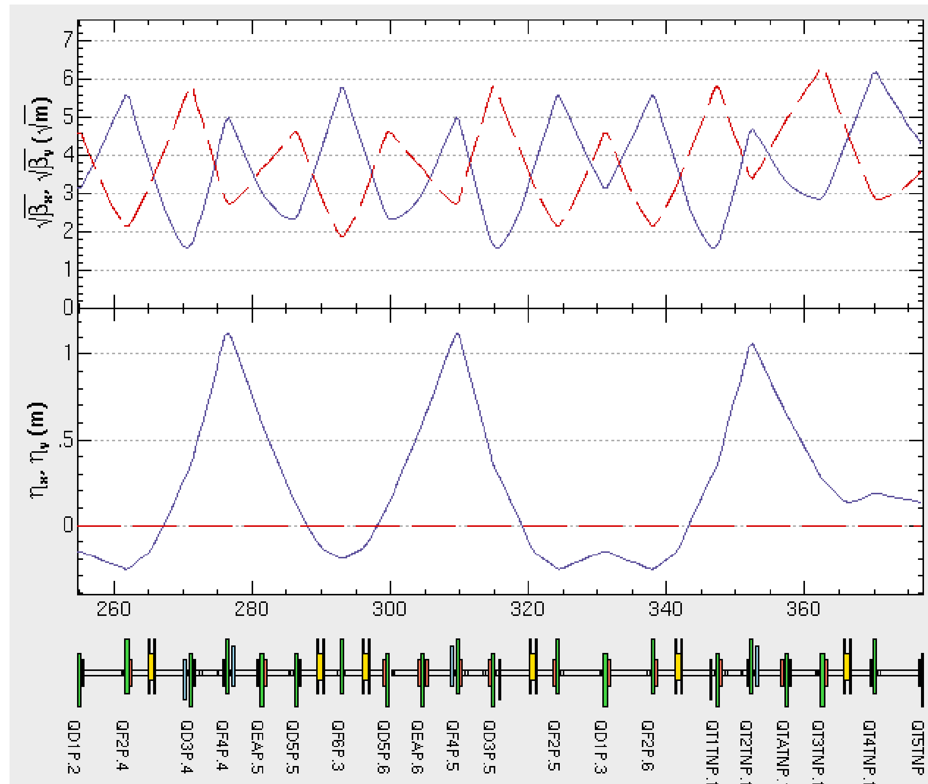
with given ν_s~ -.0224

  - To shorten the bunch length
- Results
  - We have succeeded to weaken the synchro-betatron resonance line in HER. We could operate the machine with $\nu_x$below the resonance lines.
  - We have successfully shorten the bunch length of both beam.
    - ~6mm -> ~4.5mm
  - However, we found unexpectedly large synchrotron oscillation in LERdue to the microwave instability and gave up the trial of the negative-αoptics.
  - Recently, we succeeded in suppressing the instability by increasing the absolute value of α.

LER Optics (cell)



Positive α



Negative α

H. Koiso

LER Optics

Positive α (now)

ε_x (m)	2.405366E-8
ε_y (m)	1.69092E-12
ε_z (m)	3.462018E-6
α	3.427292E-4
σ_z (mm)	4.76398
$\delta p/p_0$	7.267525E-4
U_0 (MV)	1.636932
$\delta V/p_0$	.024086
C (m)	3016.242600
Δs (m)	-.021358
f (Hz)	508890559.63
Δf (Hz)	-3603.462408
ν_s	-.0250
Crabing_{IP} (mrad)	.0000

$\Delta f'$ (Hz)	.0	.0
V_c (MV)	8.00000	8.00000
V_{crab} (MV)	.00000	.00000
ϕ_{crab} (deg)	.000	.000

Negative α

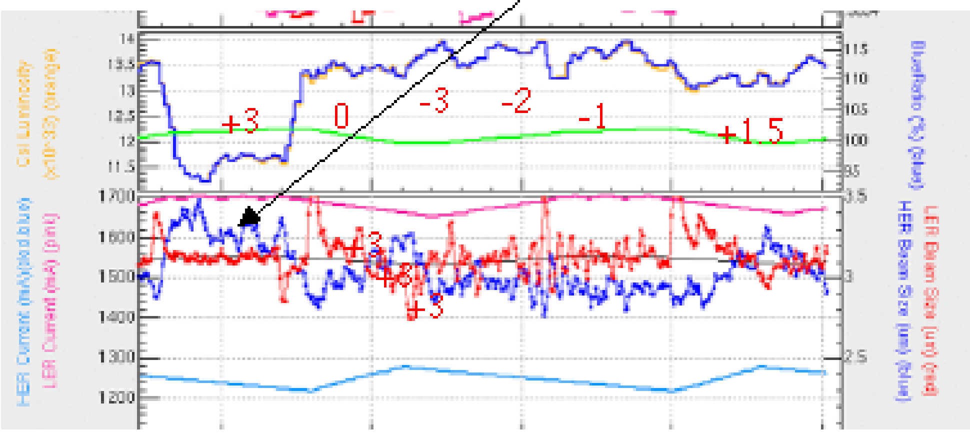
ε_x (m)	2.306358E-8
ε_y (m)	1.69102E-12
ε_z (m)	2.988536E-6
α	-2.54641E-4
σ_z (mm)	4.11190
$\delta p/p_0$	7.268836E-4
U_0 (MV)	1.636932
$\delta V/p_0$	.037472
C (m)	3016.242600
Δs (m)	-.021358
f (Hz)	508890559.63
Δf (Hz)	-3603.462408
ν_s	.0215
Crabing_{IP} (mrad)	.0000

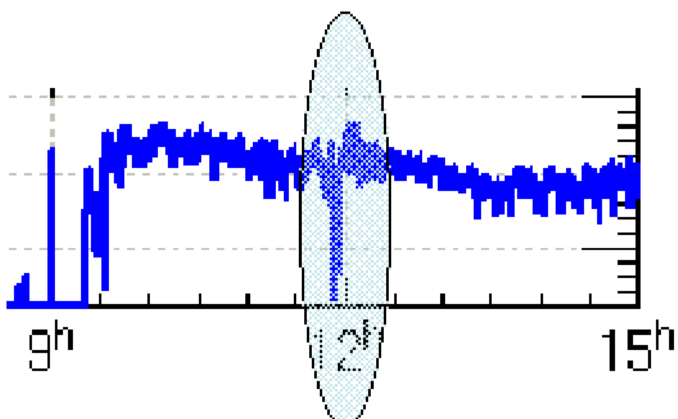
$\Delta f'$ (Hz)	.0	.0
V_c (MV)	-8.00000	-8.00000
V_{crab} (MV)	.00000	.00000
ϕ_{crab} (deg)	.000	.000

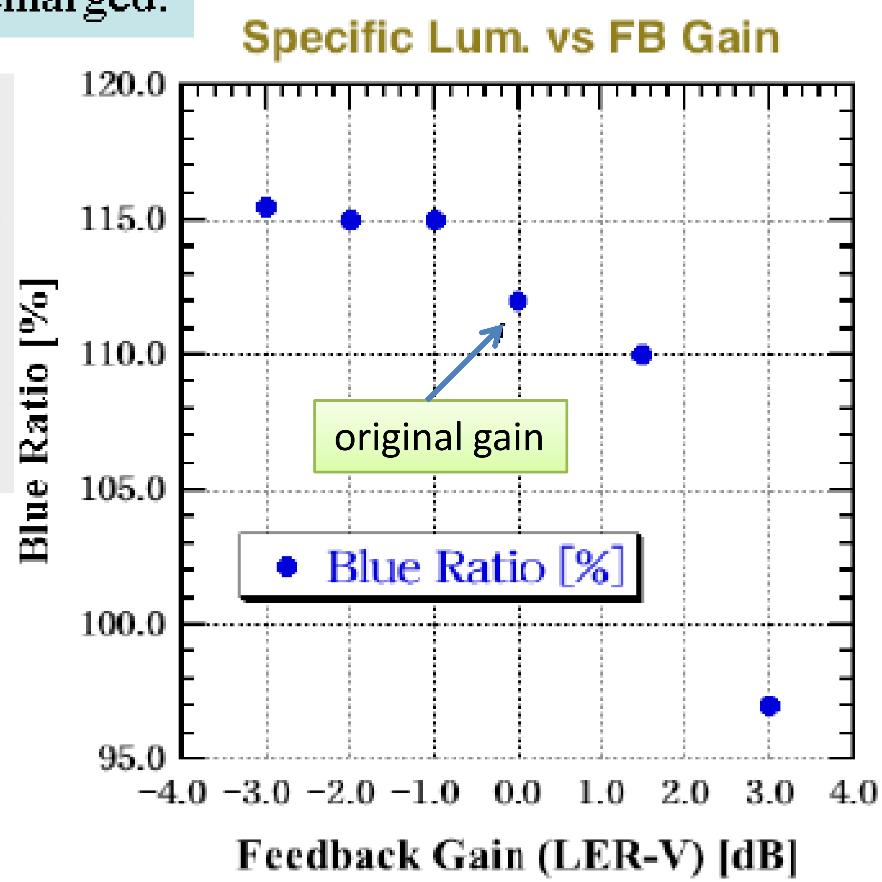
Noise of feedback system affected luminosity? (22mrad crossing angle)

2005/June/06

HER vertical size enlarged.





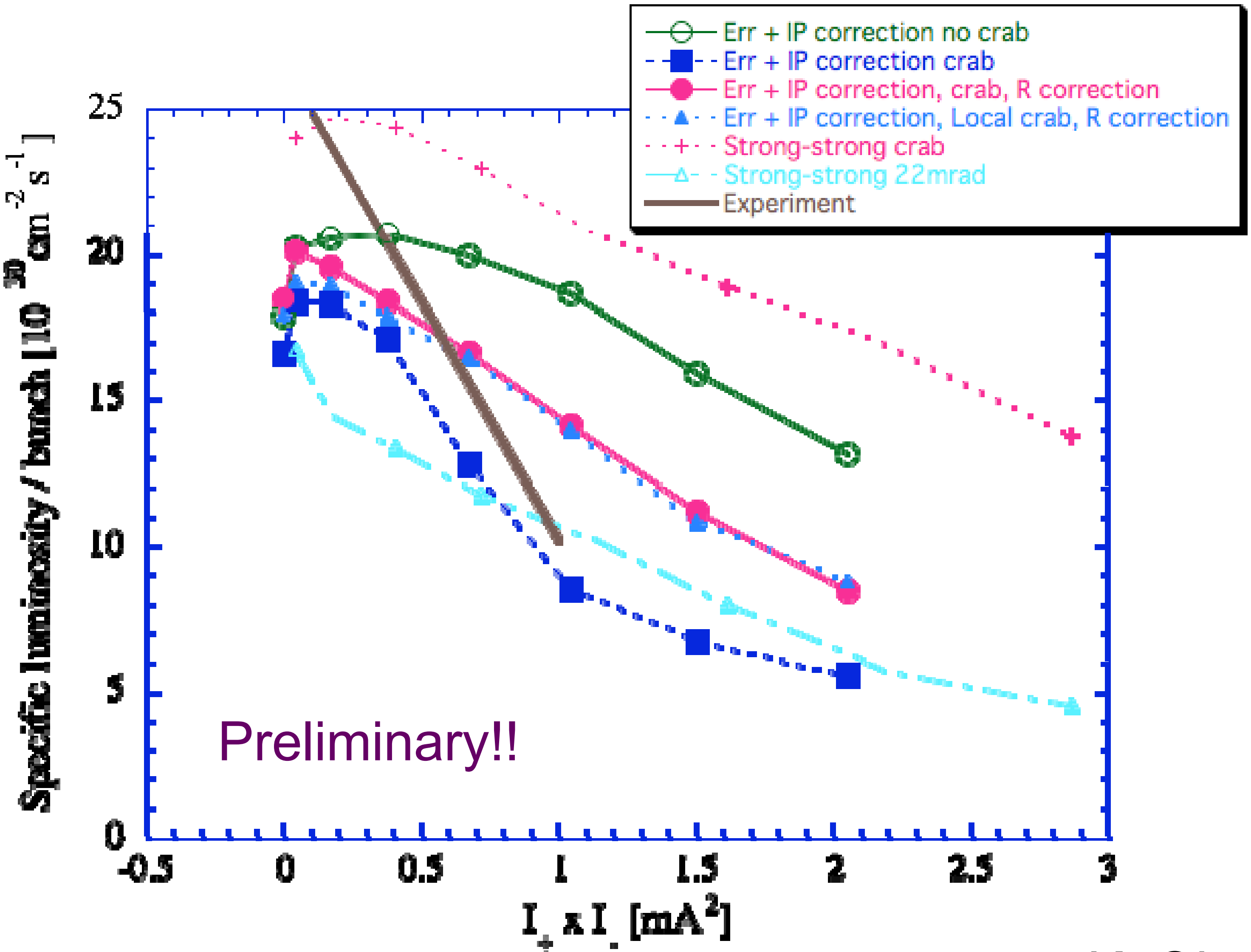


★We once found that the luminosity increased by lowering the gain of bunch-by-bunch feedback system (LER vertical) in case of 22mrad crossing angle.

★It seemed that some noise from the FB system affected the luminosity.

★At present, no remarkable effect of FB gain is observed.

Latest beam-beam simulation



K. Ohmi

Some experience of crab cavity operation with beams

Phase stability of crab cavities

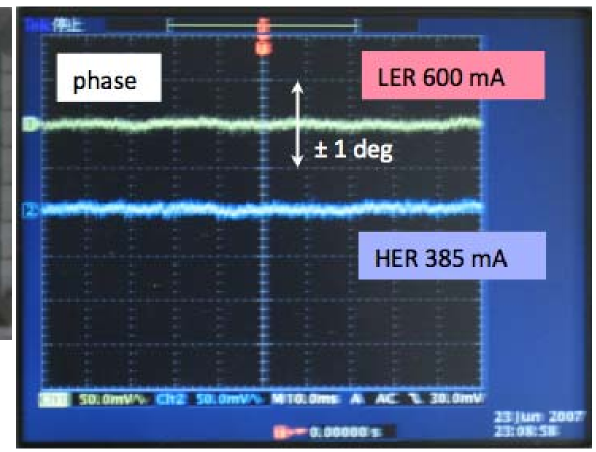
- Two measurements with different signals (cavity pick up signal and signal from phase detector of PLL) give a consistent result.
- Phase fluctuation faster than 1 kHz is less than ±0.01°, and slow fluctuation from ten to several hundreds Hz is about ±0.1°.
- They are much less than the allowed phase error obtained from the beam-beam simulations for the crabbing beams in KEKB.

Span 200 kHz
Sideband peaks at 32kHz and 64kHz.

Span 10 kHz

Span 500 Hz
Sideband peaks at 32, 37, 46, 50, 100 Hz.

Spectrum around the crabbing mode measured at a pick up port of the LER crab cavity. Beam current was between 450 and 600 mA.

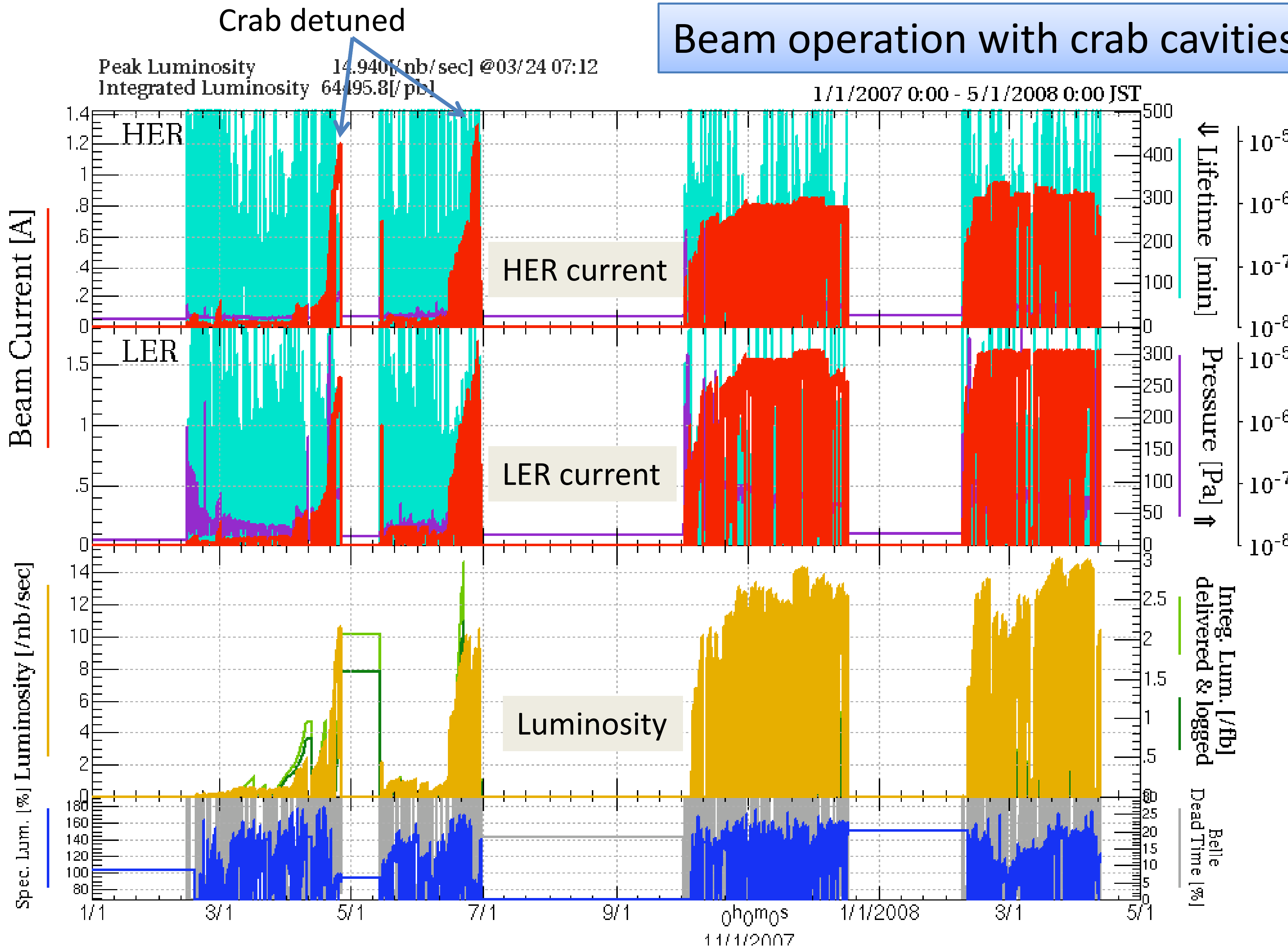


Phase detector signal. Beam current was 385mA (HER) and 600 mA (LER).

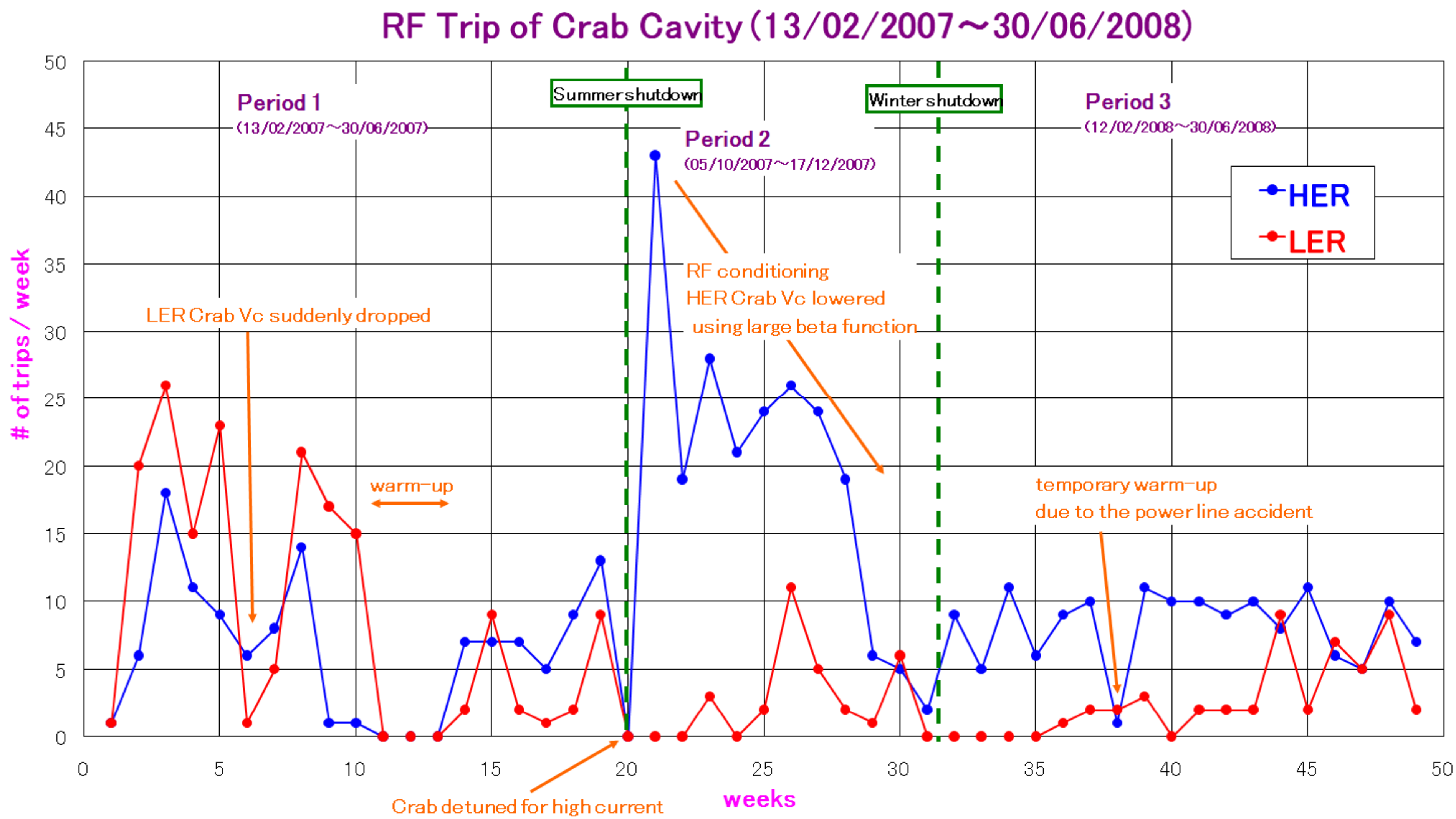
According to beam-beam simulation by K. Ohmi, allowed phase error for N-turn correlation is $0.1\times\sqrt{N}$ (degree).
The measured phase errors are much smaller than the allowed values given by beam-beam simulation.

K. Akai

Beam operation with crab cavities



Trip rate of crab cavities



Summary

- 20 years after they were initially proposed, in February 2007 crab cavities are for the first time installed in an operating collider, KEKB.
- The crab cavities at KEKB have been working much more stably than the initial expectation.
  - They are presently being used in usual physics run (high beam current!!).
- The success of the development of the crab cavities is important, since they can be applied to other machines such as SR facilities or an upgrade of LHC.
- With crab crossing, the vertical beam-beam parameter of 0.093 was obtained. This indicates superiority of crab crossing scheme.
- However, the crab cavity at KEKB has not yet fully realized its potential capability in the sense that the specific luminosity is much lower than the beam-beam simulation at the high bunch currents.
- Finding the cause of this problem is very important for KEKB, since the design of SuperKEKB already counts the luminosity gain by the crab cavities.

Future plans

- We will continue the investigation on the low specific luminosity at high bunch currents.
- More beam-beam simulation (Ohmi)
- In the autumn run this year, the e+ and e- simultaneous injection may be realized at KEKB. It is expected that the beam operation with shorter beam lifetime will be possible. Some luminosity gain is expected with this.
- KEKB maybe continue its operation also in the next fiscal year (Apr. 2009~).

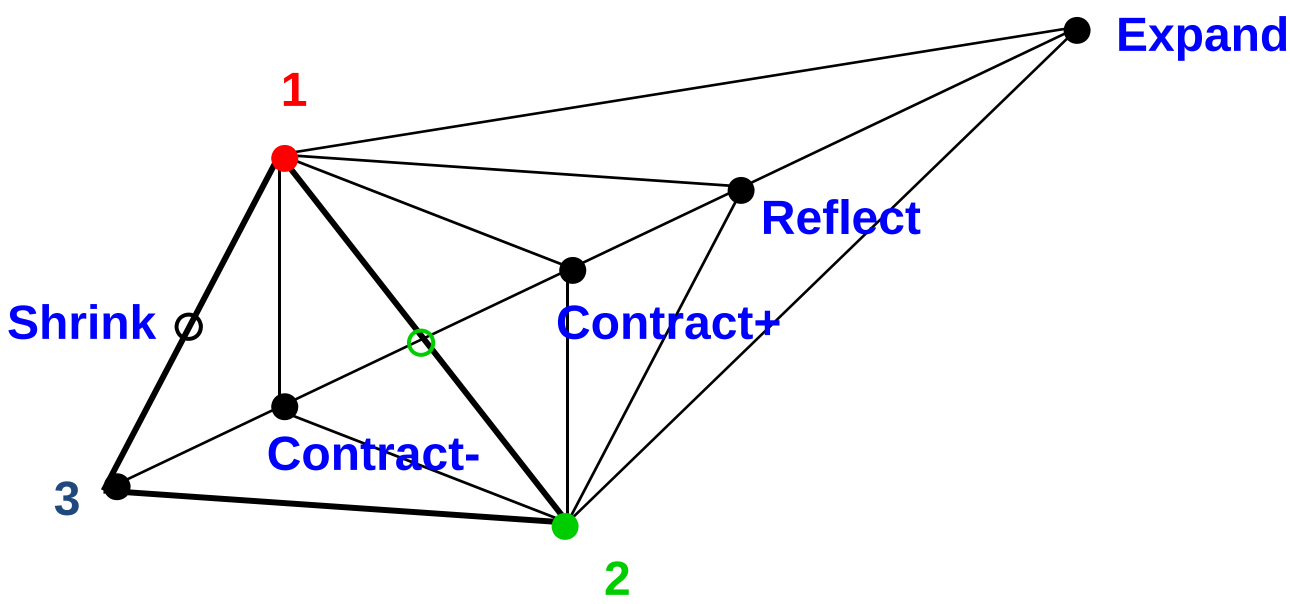
Spare slides

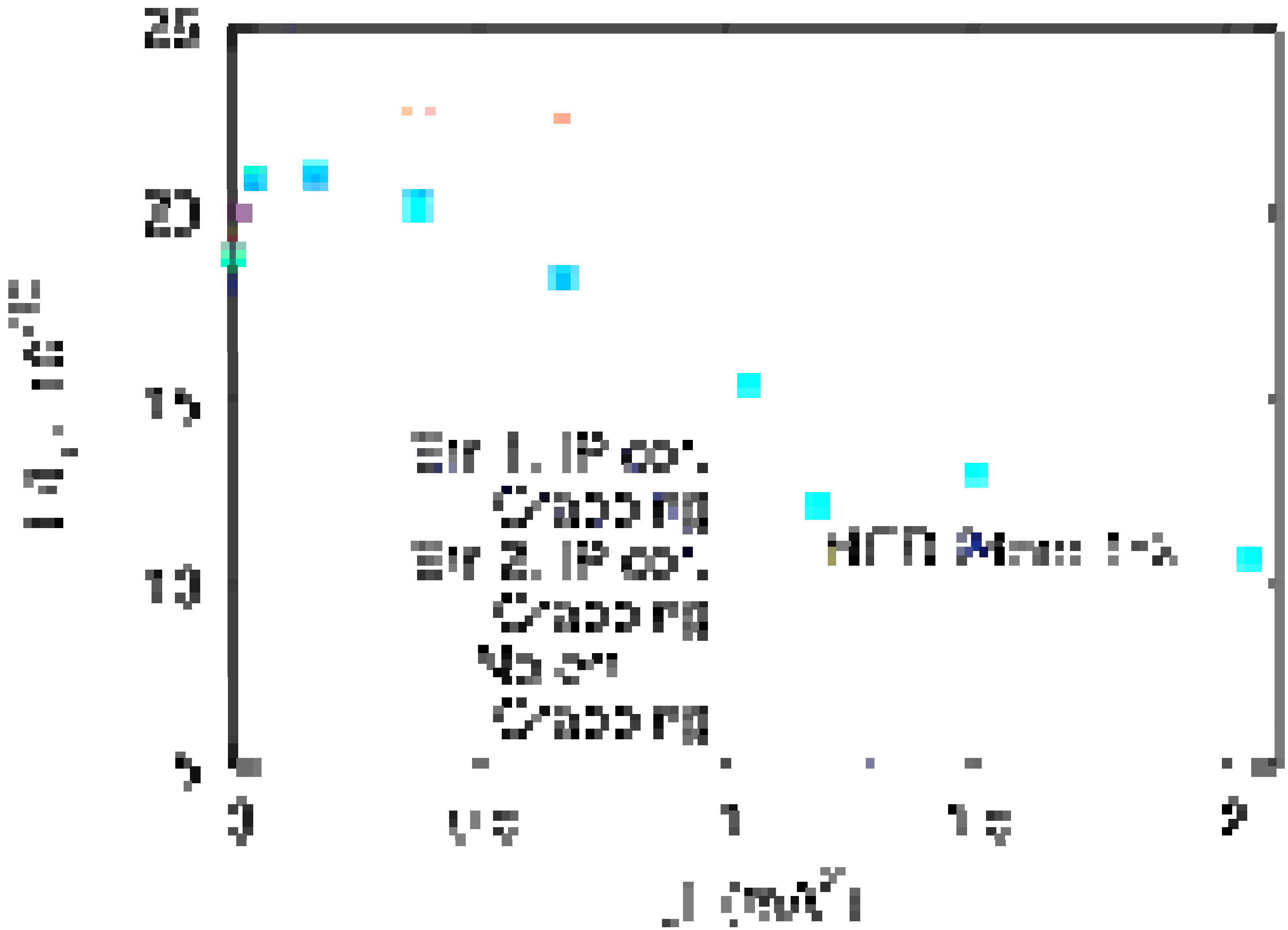
Downhill Simplex Method

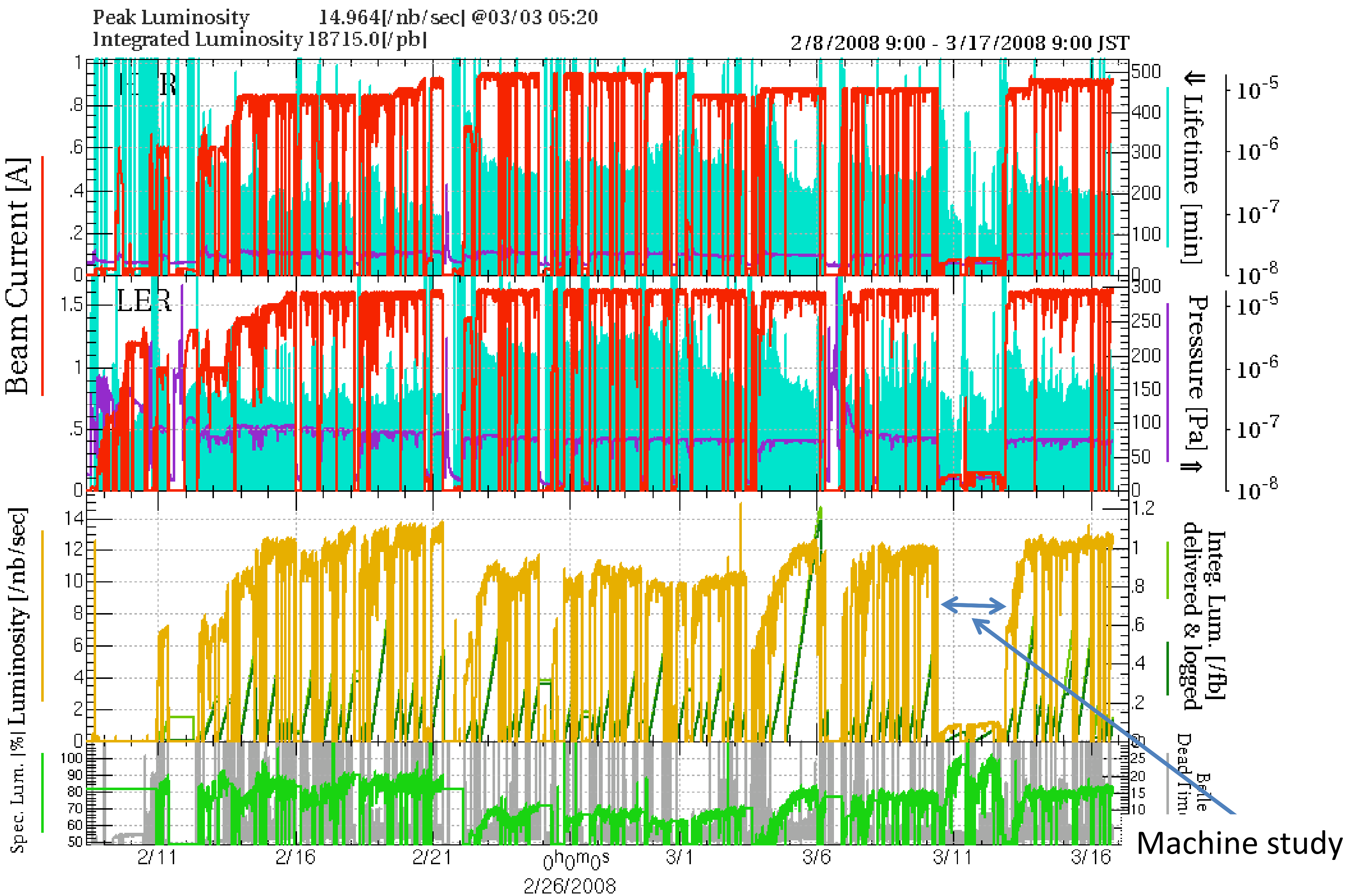
H. Koiso

Method of Minimization

- {1, 2, 3} 1(best)<2(next-to-the worst)<3(worst)
- Evaluate 3_R
- If 3_R<1,
  - If 3_E<3_R, {1, 2, 3_E} : Expand , if not,{1, 2, 3_R} : Reflect
- If 1<3_R<2, {1, 2, 3_R} : Reflect
- If 2<3_R<3, Reflect 2 proposed by A. Hutton
  - If 3_{C+}<3_R, {1, 2, 3_{C+}} : Contract+ , if not,{1, 2, 3_R} : Reflect
- If 3<3_R, Reflect 2
  - If 3_{C-}<3, {1, 2, 3_{C-}} : Contract- , if not, {1, 2_S, 3_S} : Shrink/Reflect2




25
20
15
10
5
0
0.5
1
1.5
2

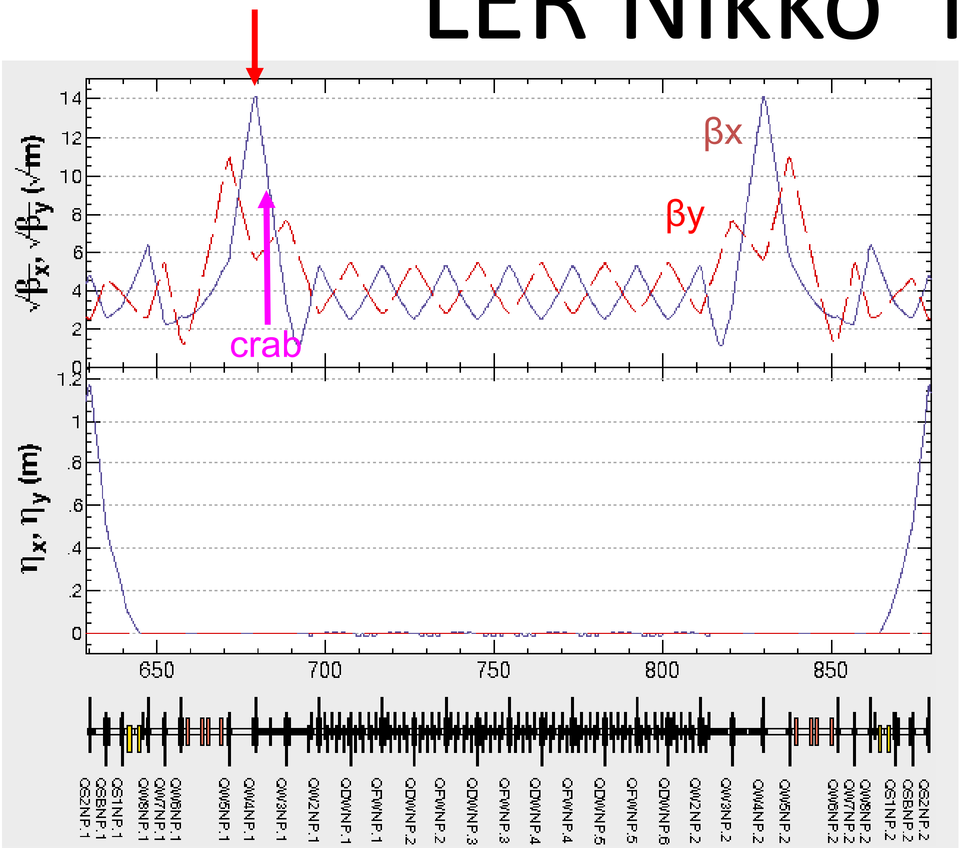


®$_x$* = 0.9m

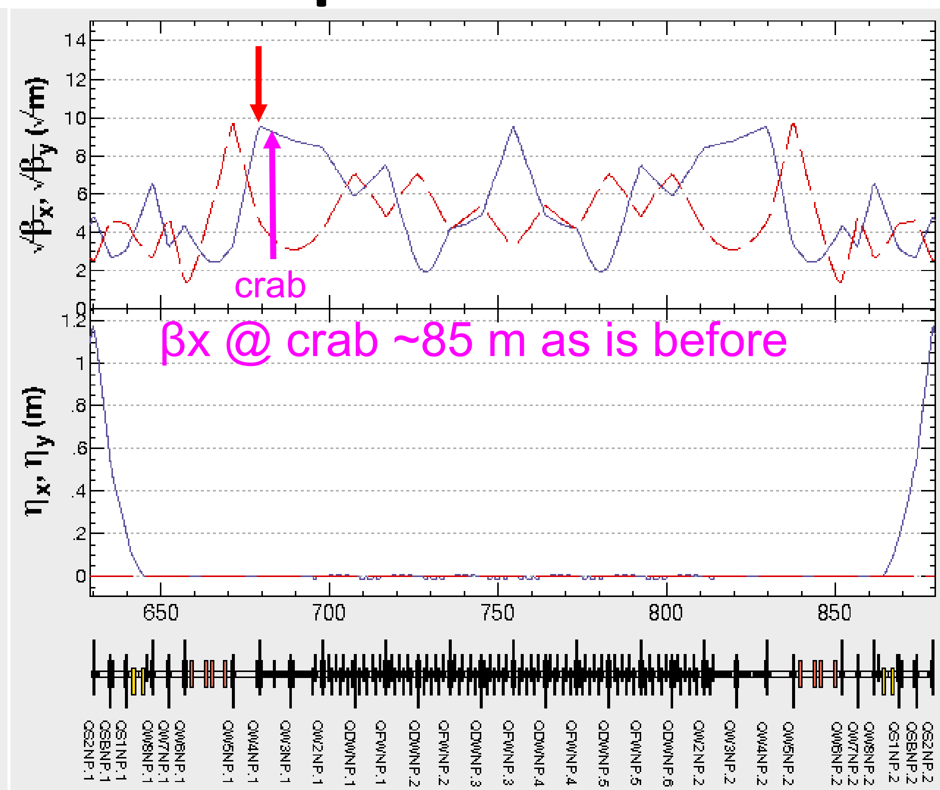
®$_x$* = LER Nikko new optics ®$_x$* = 1.5m ®$_x$* =

H. Koiso

LER Nikko New Optics

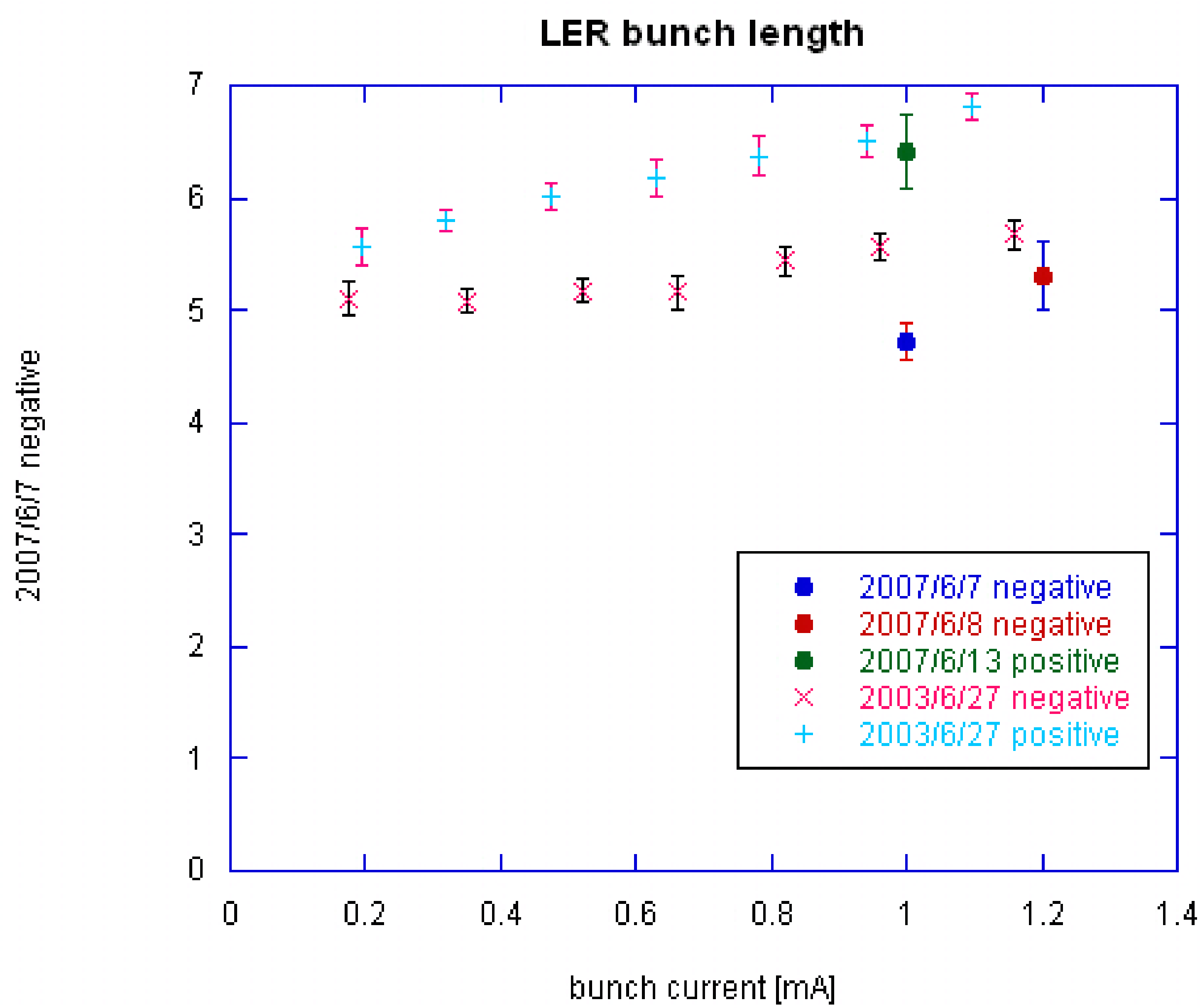


Before 2/21(maintenance)
βx max 199 m
(νx,νy)=(45.505,43.59)



After 2/21(maintenance)
βx max 91 m
(νx,νy)=(44.505,43.59)
Large β distortion in wiggler section

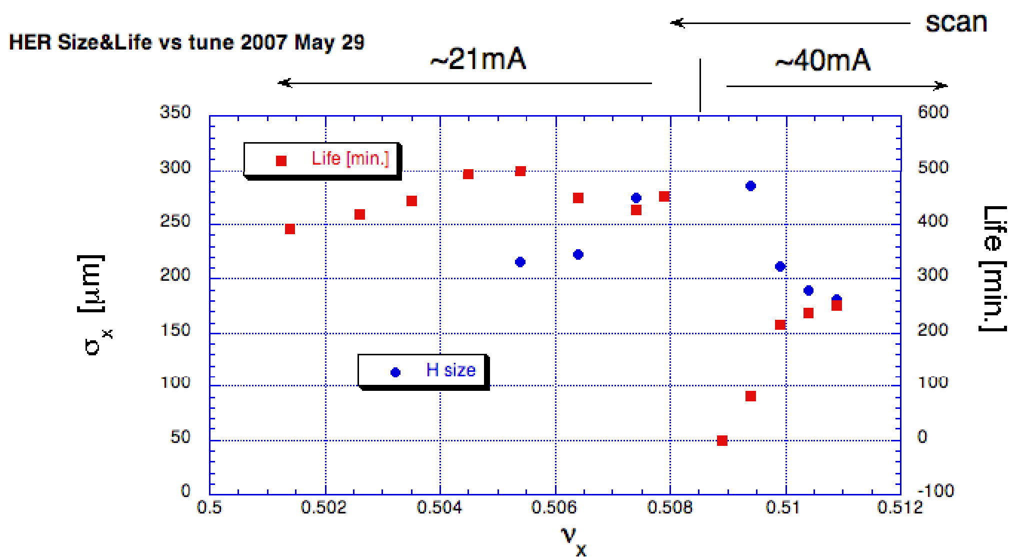
Bunchlength measurement

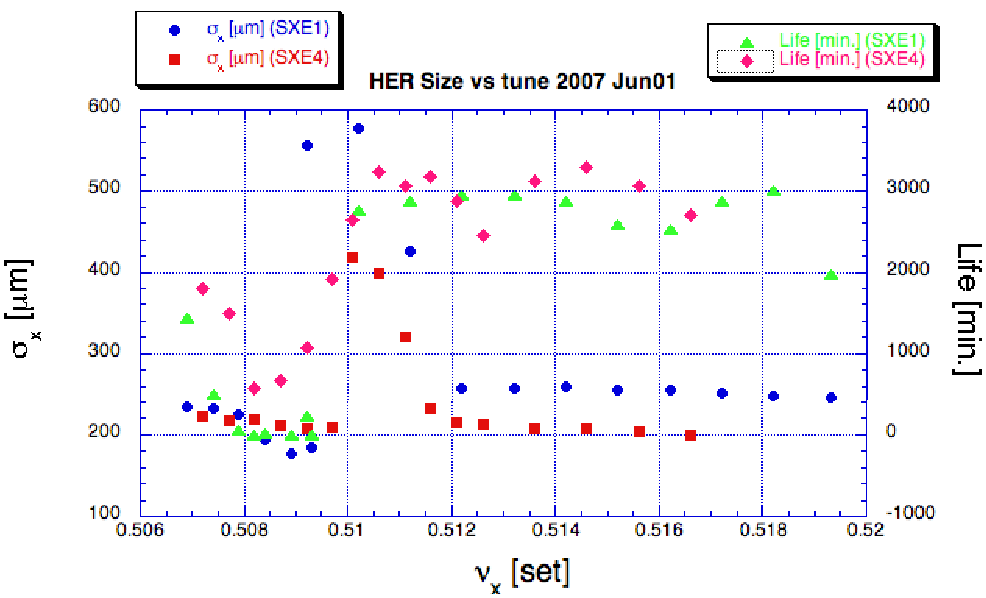


α= -2.55E-4
α= -2.55E-4
〈= +3.31E-4
〈= -3.41E-4
〈= +3.41E-4

H. Ikeda

Synchro-betatron resonance in HER

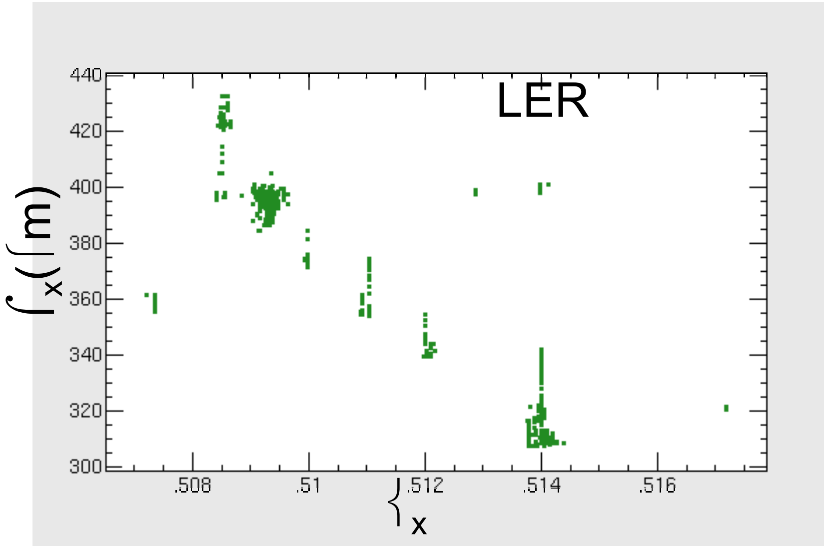


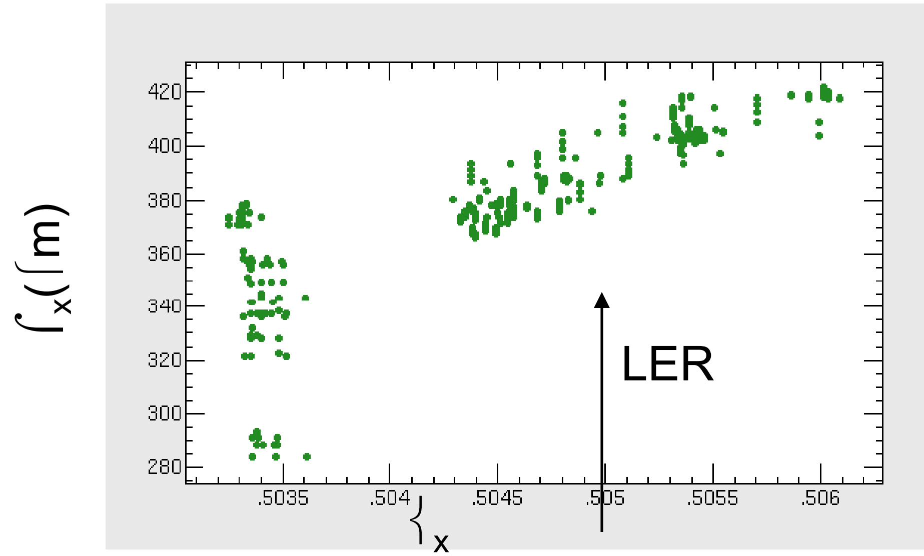


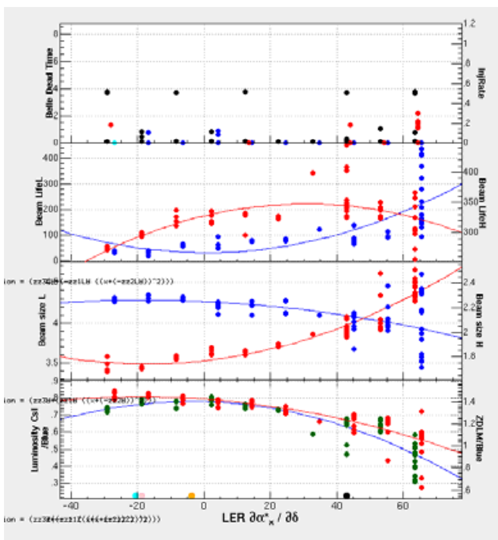
- Positive-ν
  - We could NOT operate under the resonance ($2\nu_x+\nu_s$=integer)

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

The luminosity depends on the sextupole setting







Chromaticity tuning

- We often observed the horizontal size changed dependent on sextuple setting.
- The luminosity is also improved with the chromaticity tuning.

Calculation of beam-beam parameter

- Reduction factor for beam-beam parameter

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

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

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

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

Montague's factor

Calculation of beam-beam parameter [cont'd]

- Reduction factor for luminosity

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

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

  - Luminosity

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

  - We use calculated values for ⌠$_x^*$ and calculate ⌠$_y^*$ and ⌊$_{y0}$from observed luminosity.