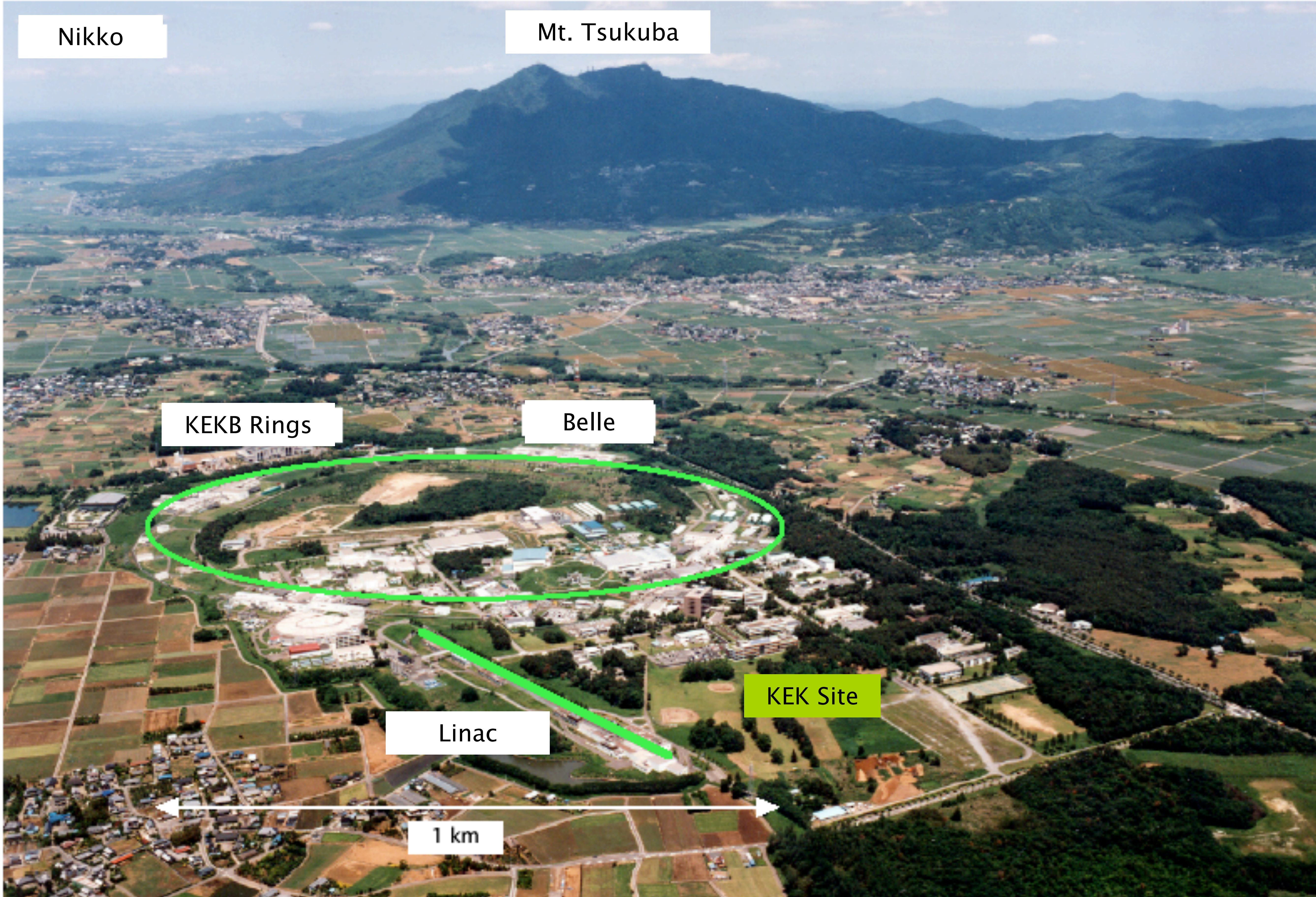
The First Experience of

Crab Crossing at KEKB

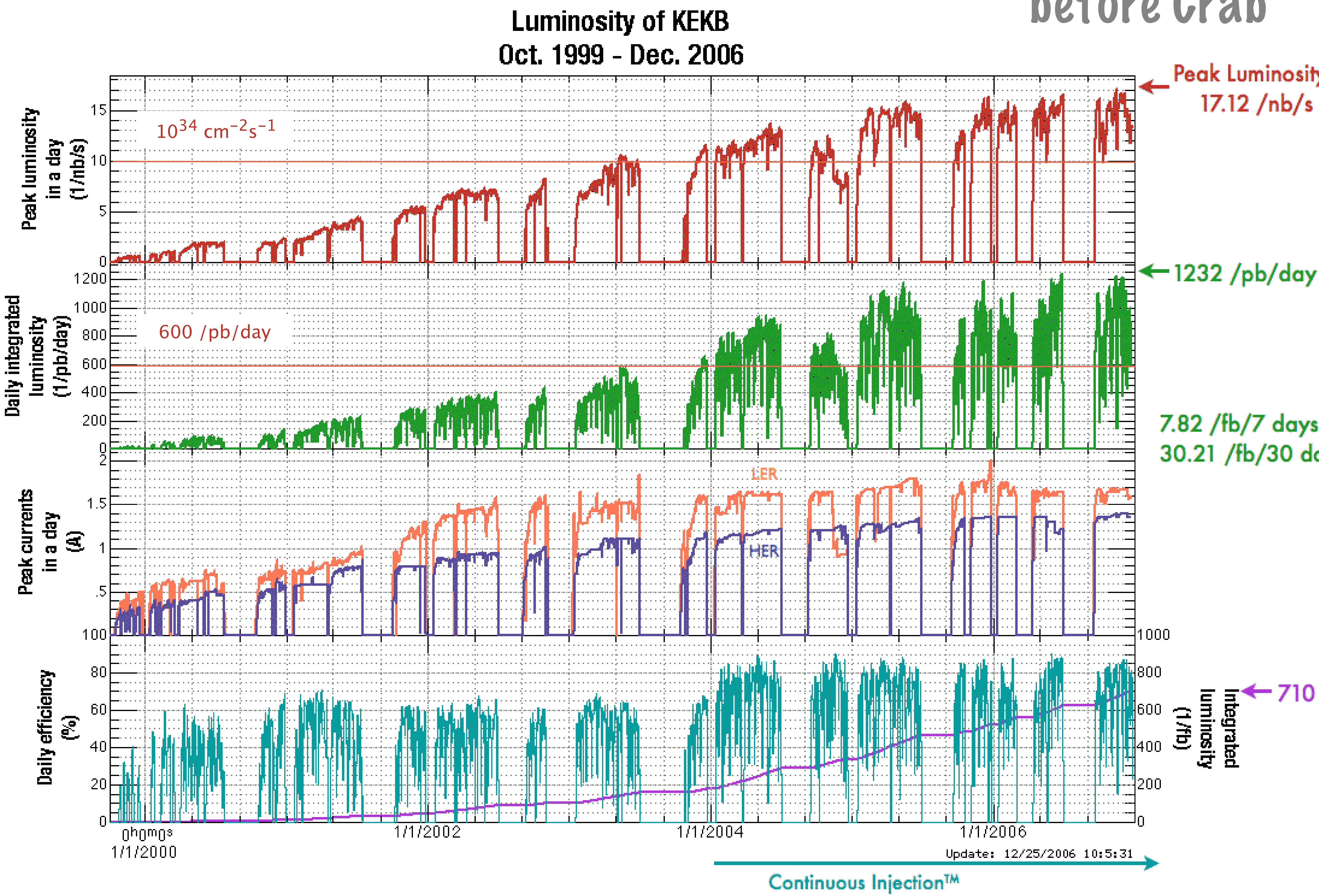
K. Oide for the KEKB Accelerator Group

25 February 2008

LHC-CC08 @ BNL


Nikko
Mt. Tsukuba
KEKB Rings
Belle
KEK Site
Linac
1 km

before Crab



Luminosity of KEKB
Oct. 1999 - Dec. 2006
Peak luminosity in a day (1/nb/s)
10^{34} cm^{-2}s^{-1}
Peak Luminosity
17.12 /nb/s
Daily integrated luminosity (1/pb/day)
600 /pb/day
1232 /pb/day
7.82 /fb/7 days
30.21 /fb/30 d
Peak currents in a day (A)
LER
HER
Daily efficiency (%)
Integrated luminosity (1/fb)
710
0h0m0s 1/1/2000
1/1/2002
1/1/2004
1/1/2006
Update: 12/25/2006 10:5:31
Continuous Injection™

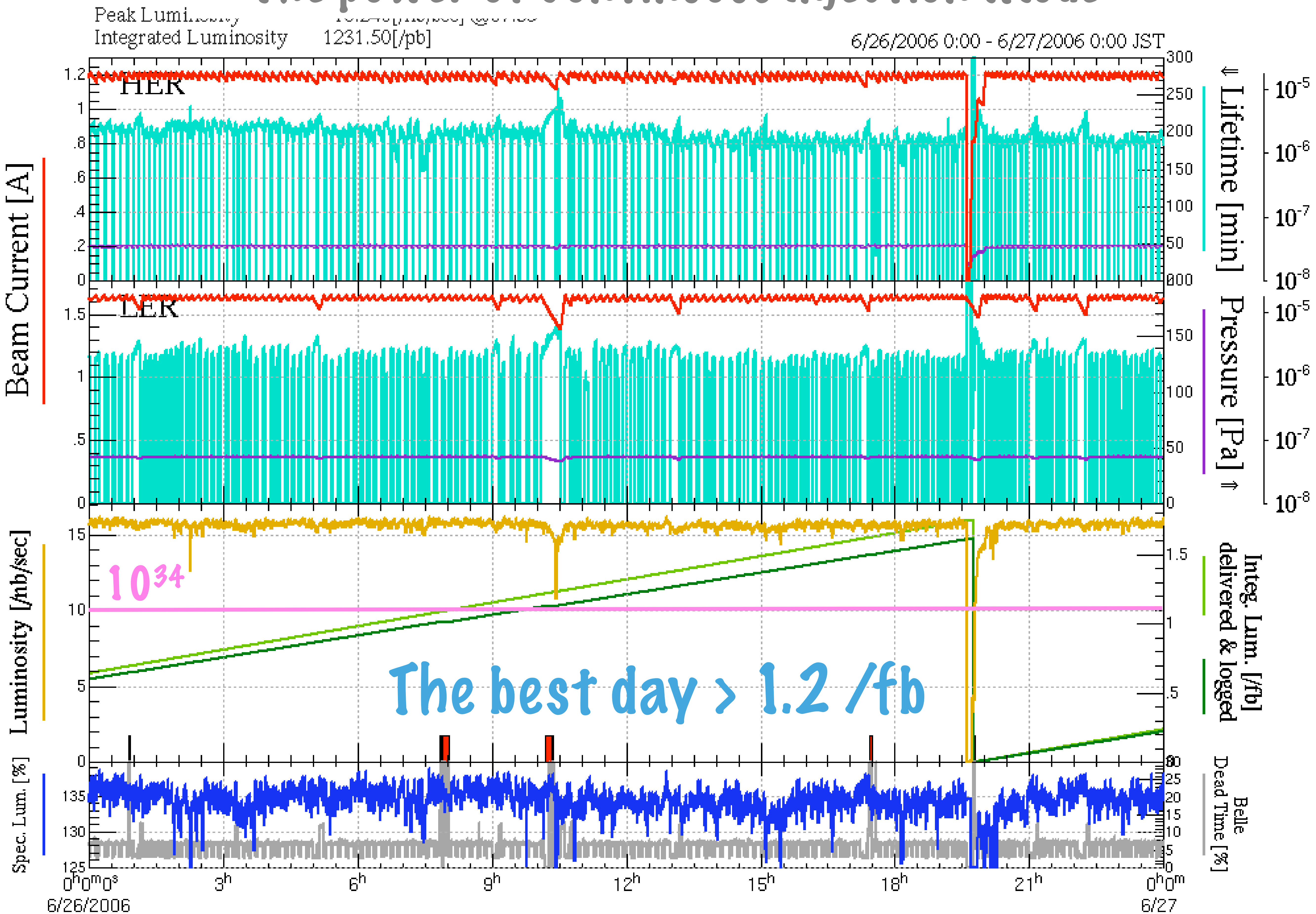
Table 1: Machine parameters of KEKB

Date	**11/15/2006**		**Design**		
	LER	**HER**	**LER**	**HER**	
Current	1.65	1.33	2.6	1.1	A
Bunches/ring	1389		5000		
Bunch current	1.19	0.96	0.52	0.22	mA
Bunch spacing	1.8–2.4		0.6		m
Emittance ε_x	18	24	18	18	nm
β_x^*	59	56	33	33	cm
β_y^*	0.65	0.59	1.0	1.0	cm
Hor. size @ IP	103	116	77	77	μm
Ver. size @ IP	1.9	1.9	1.9	1.9	μm
Beam-beam ξ_x	0.115	0.075	.039	.039	
Beam-beam ξ_y	0.101	0.056	.052	.052	
Bunch length	7	6	4	4	mm
Luminosity	17.12		10		/nb/s
$\int$Lum./day	1232		~ 600		/pb
$\int$Lum./7 days	7.82		–		/fb
$\int$Lum./30 days	30.21		–		/fb

70% higher than the design

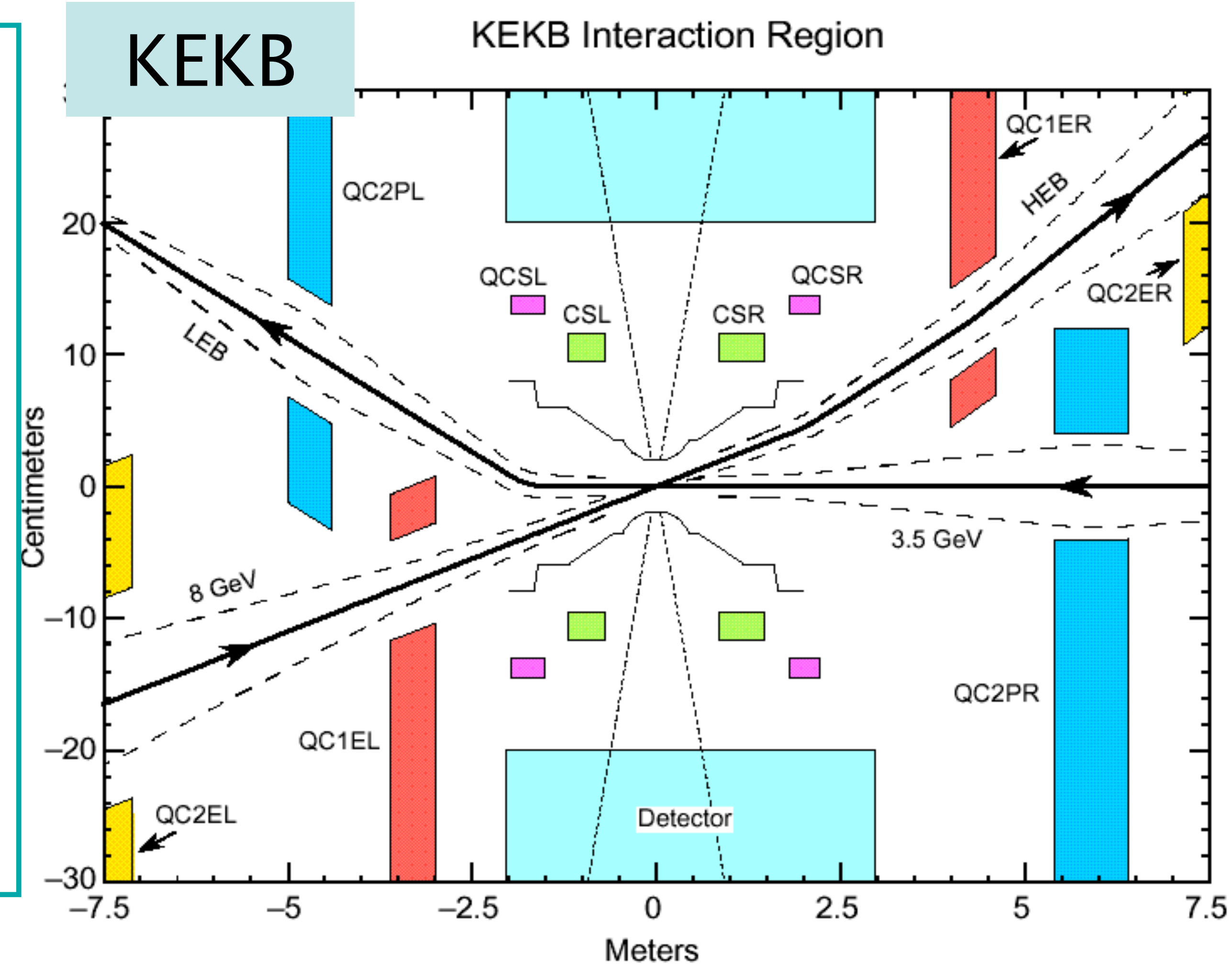
doubled the design

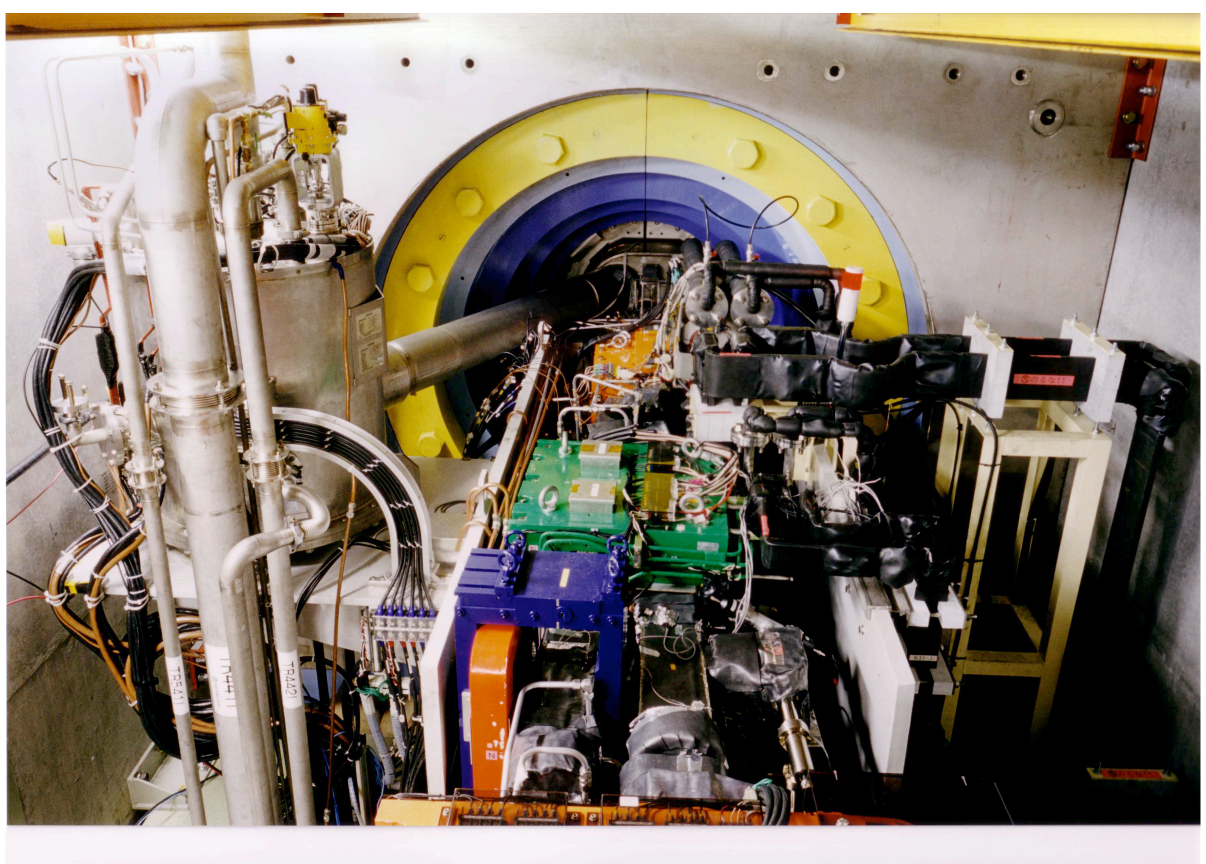
The power of Continuous Injection Mode

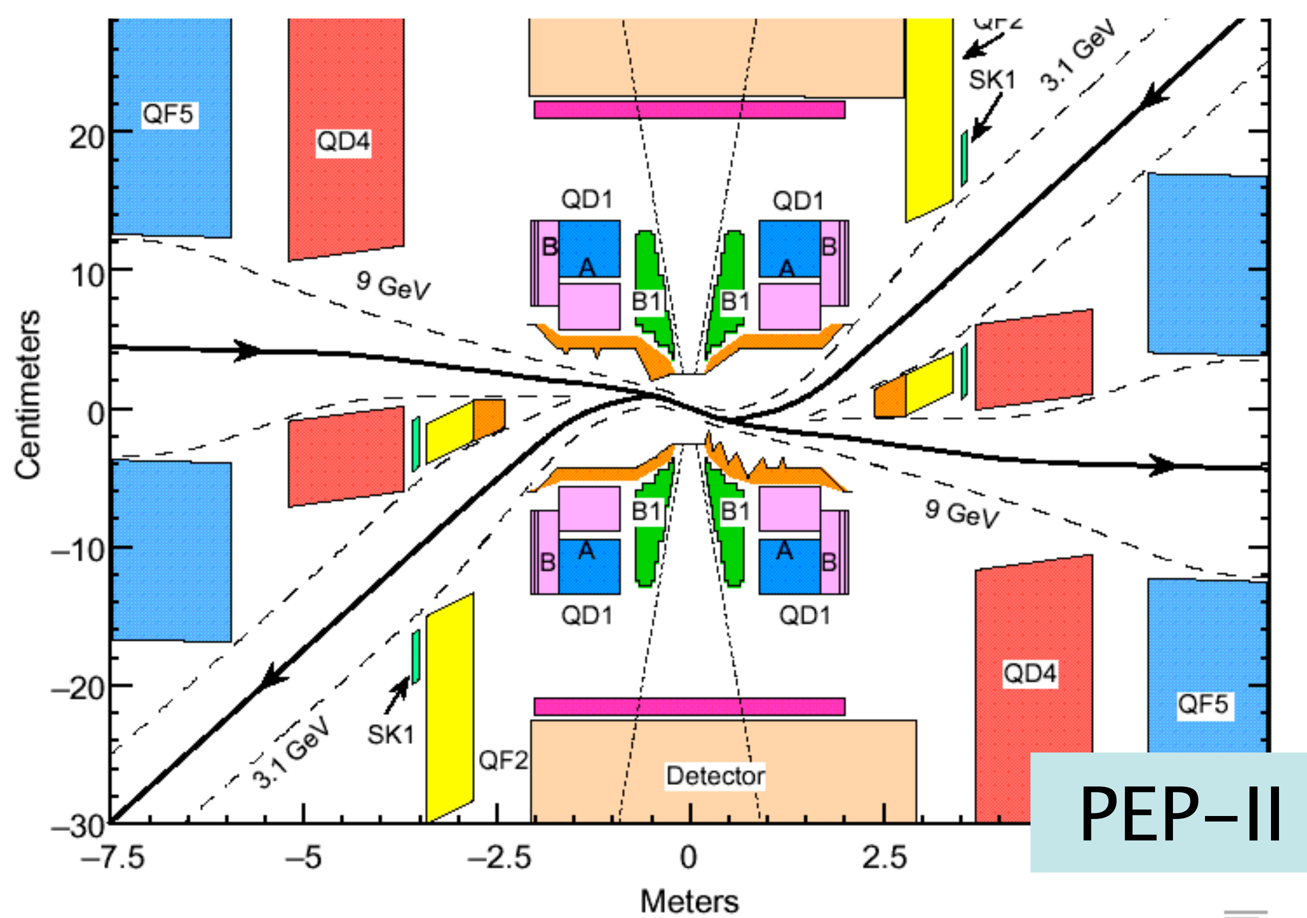


KEKB has 22 mrad horizontal crossing angle at the IP:

- •Easier beam separation
- •Simpler design around the IP.
- •Less number of components.
- •Less synchrotron radiation.
- •Less luminosity-dependent background.
- •Space for compensation solenoid, etc.



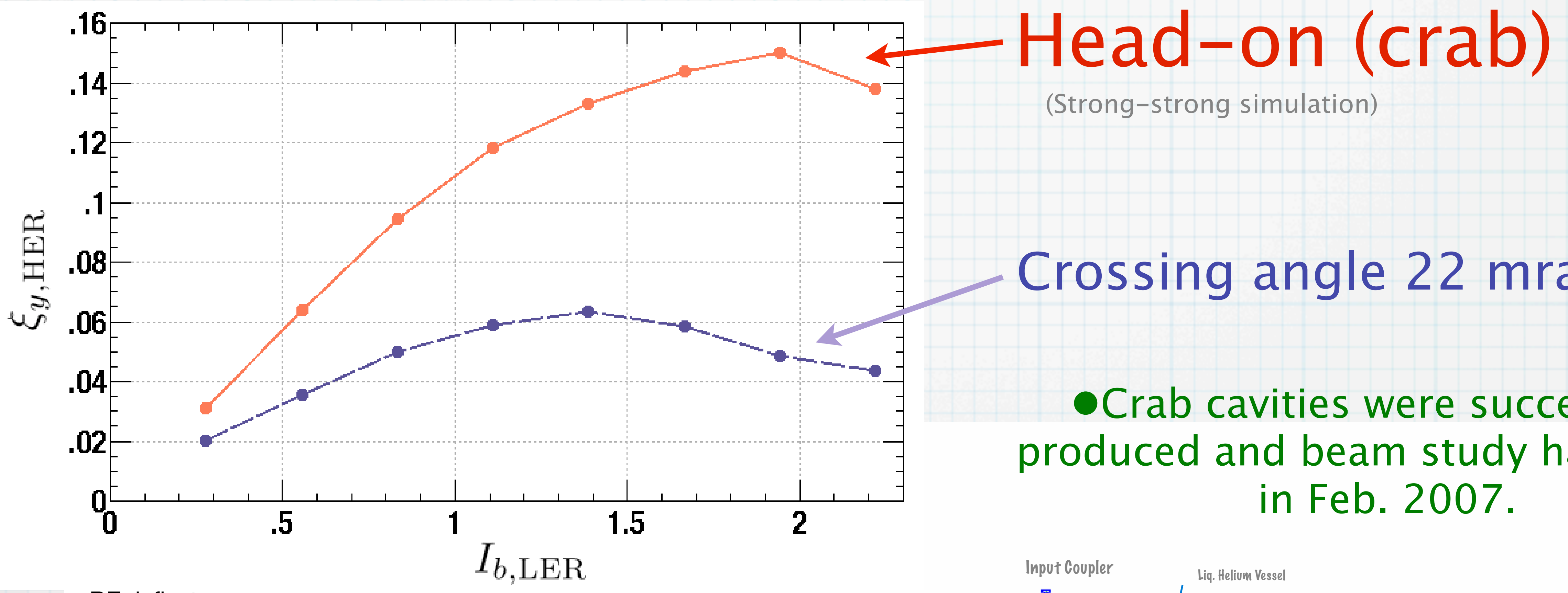




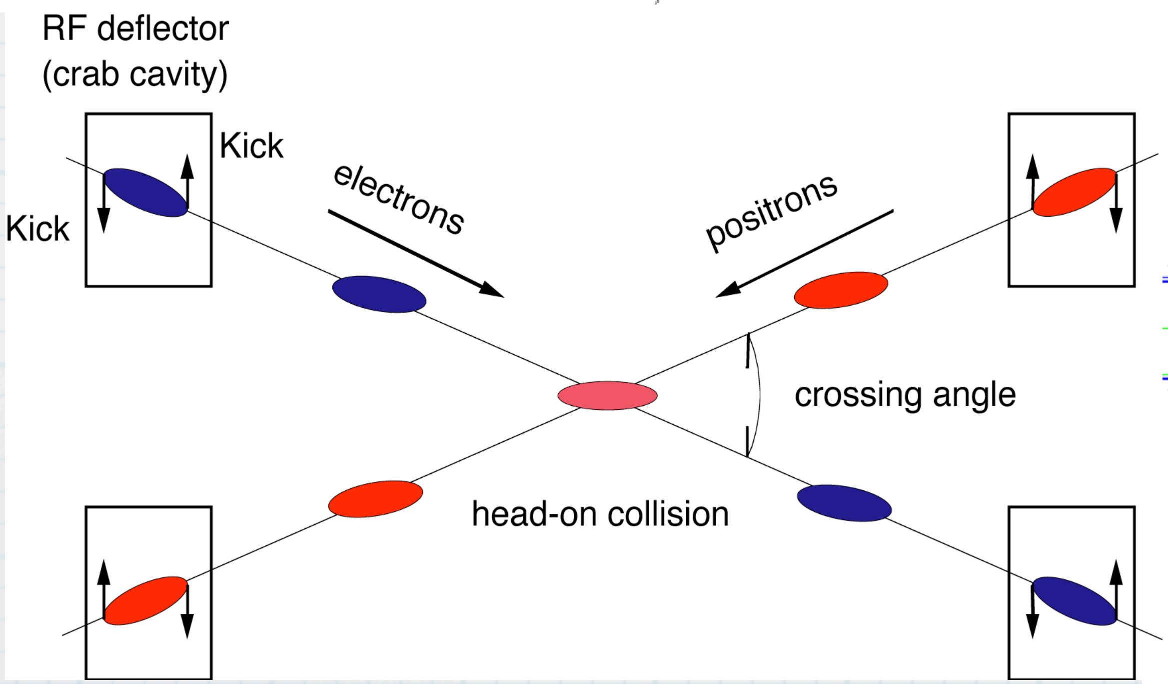
Crab Crossing @ KEKB

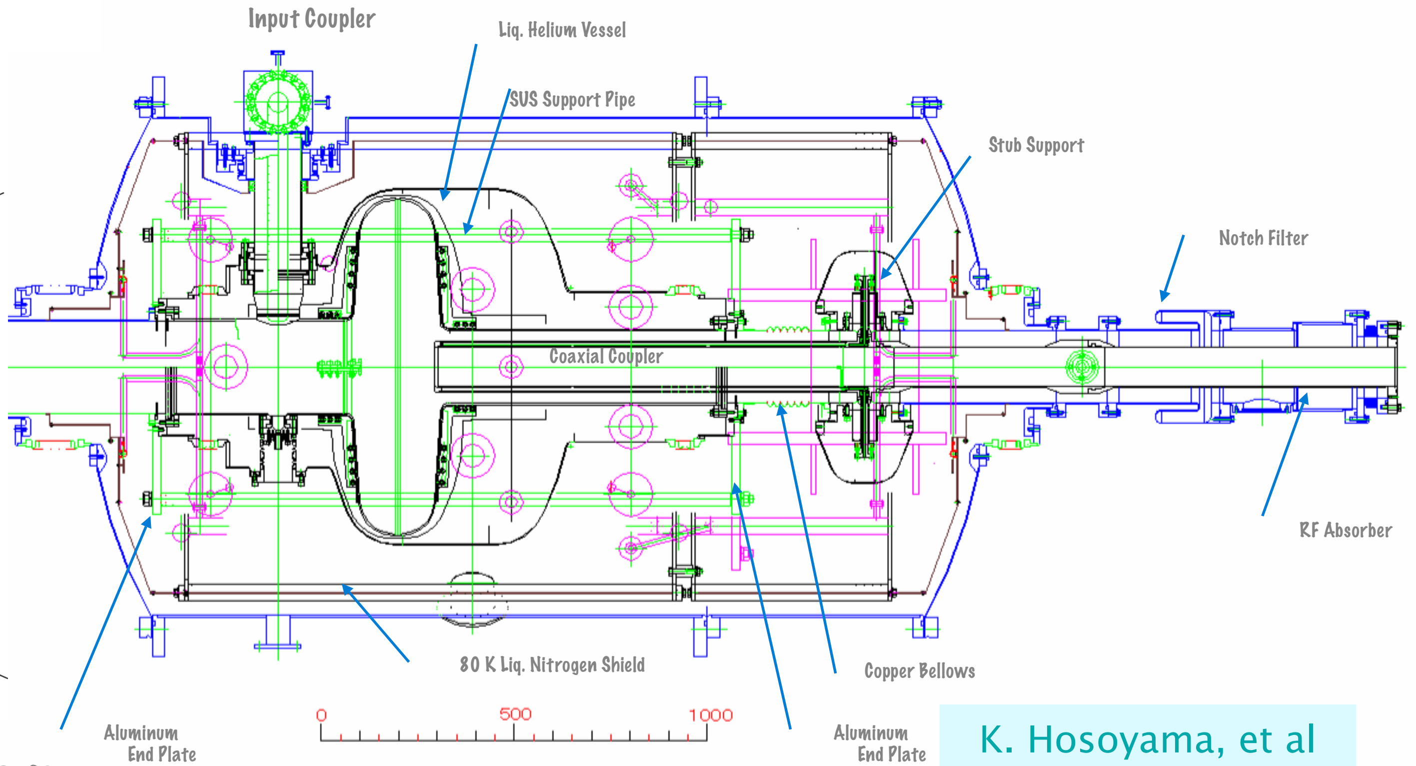
- Crab Crossing can boost the beam-beam parameter higher than 0.15 !

K. Ohmi



- Crab cavities were successfully produced and beam study has started in Feb. 2007.



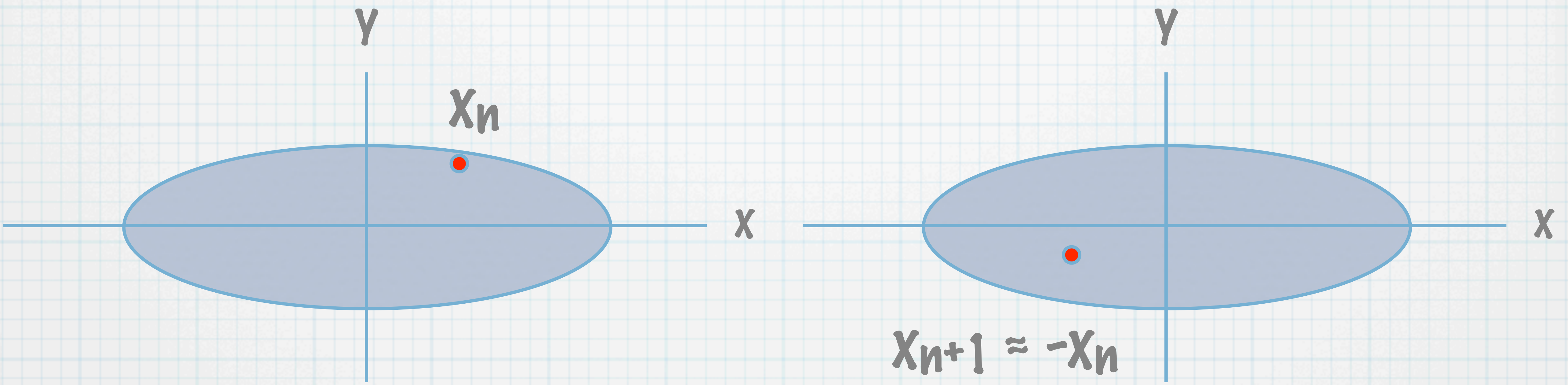


K. Hosoyama, et al

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

More gain than geometrical overlap is expected:

Head-on + hor. half integer tune
≈ 1D + synchrotron motion

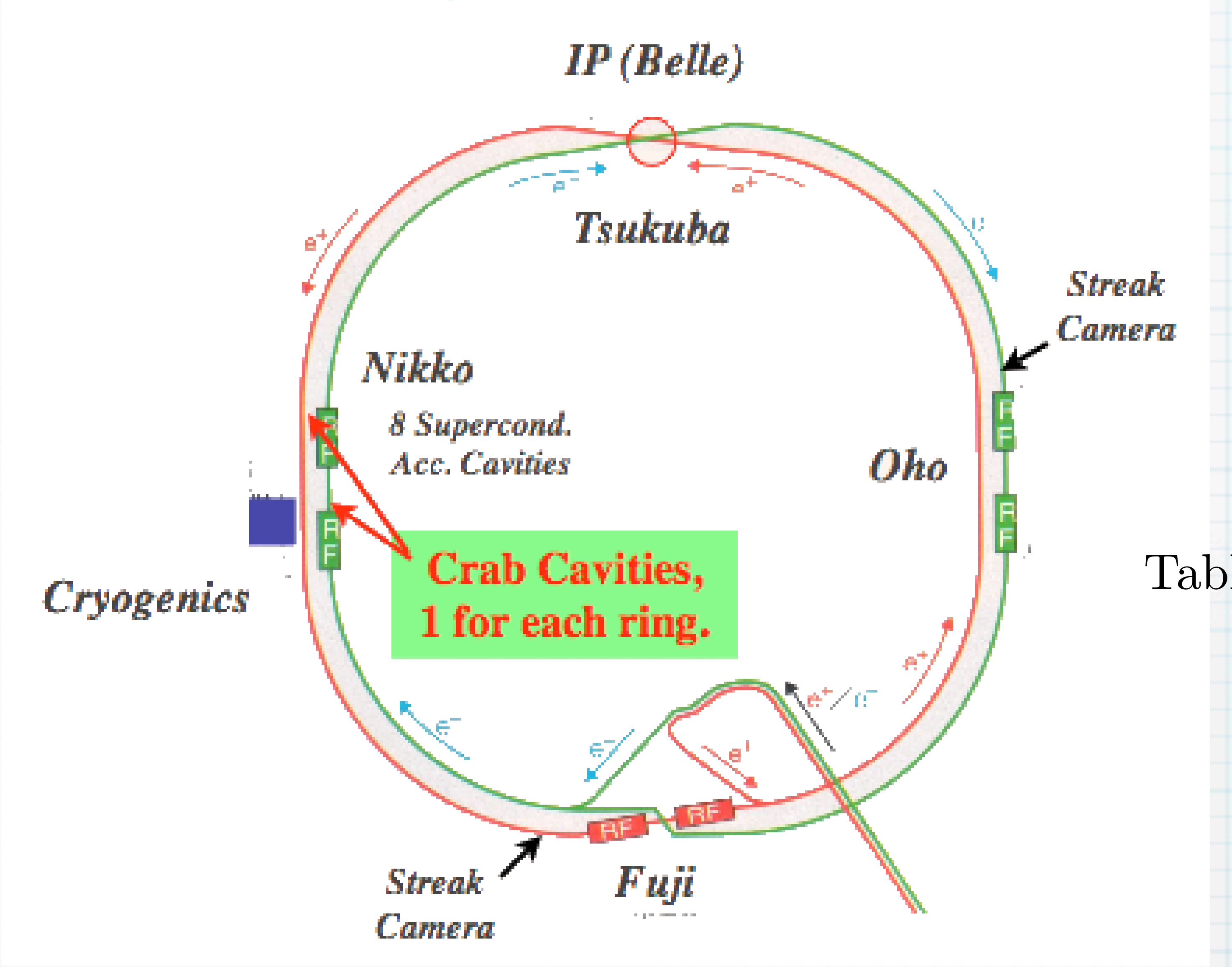


head-on: beam distribution is symmetric in x.

The beam-beam force becomes nearly independent on x at horizontal half integer and with head-on collision

(Ohmi & Perevedentsev)

Single Crab Cavity Scheme



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

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

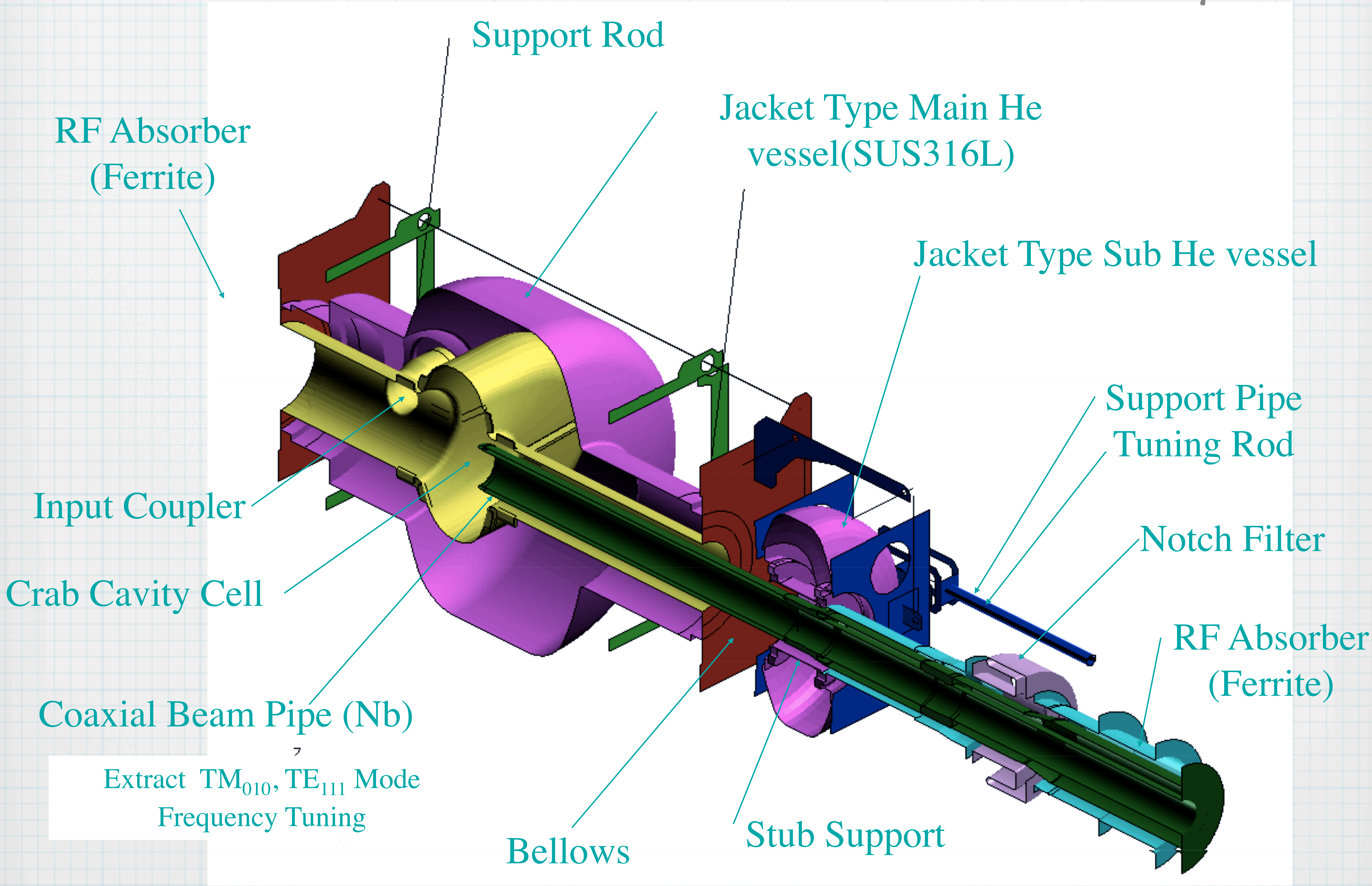
Table 1: Typical parameters for the crab crossing.

Ring	LER	HER	
θ_x	22		mrad
β_x^*	80	80	cm
β_x^C	73	162	m
$\mu_x/2\pi$	0.505	0.511	
$\psi_x^C/2\pi$	~ 0.25	~ 0.25	
V_C	0.95	1.45	V
$\omega_{\rm rf}/2\pi$	509		MHz

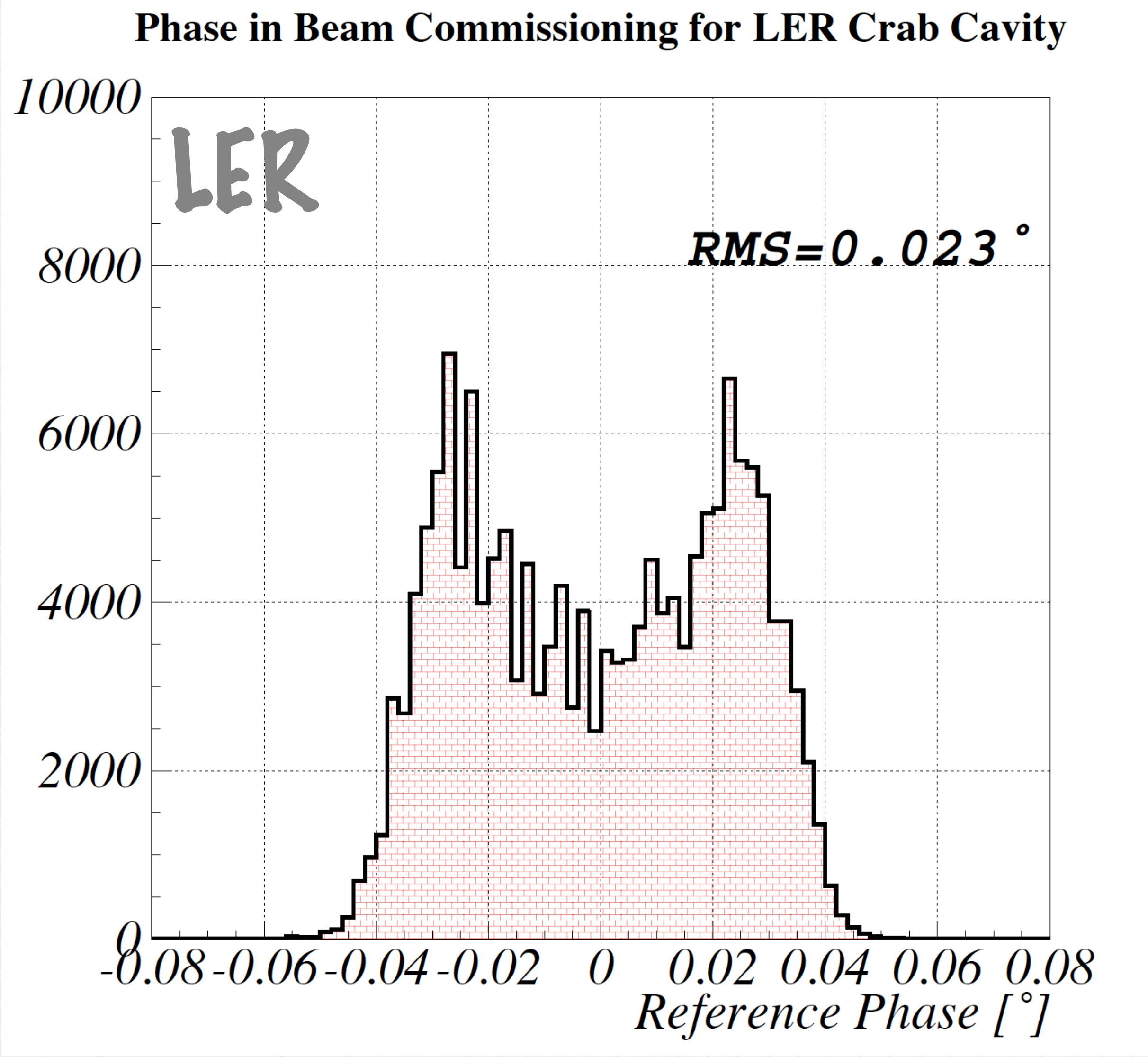
- 1 crab cavity per ring.
- saves the cost of the cavity and cryogenics.
- avoids synchrotron radiation hitting the cavity.

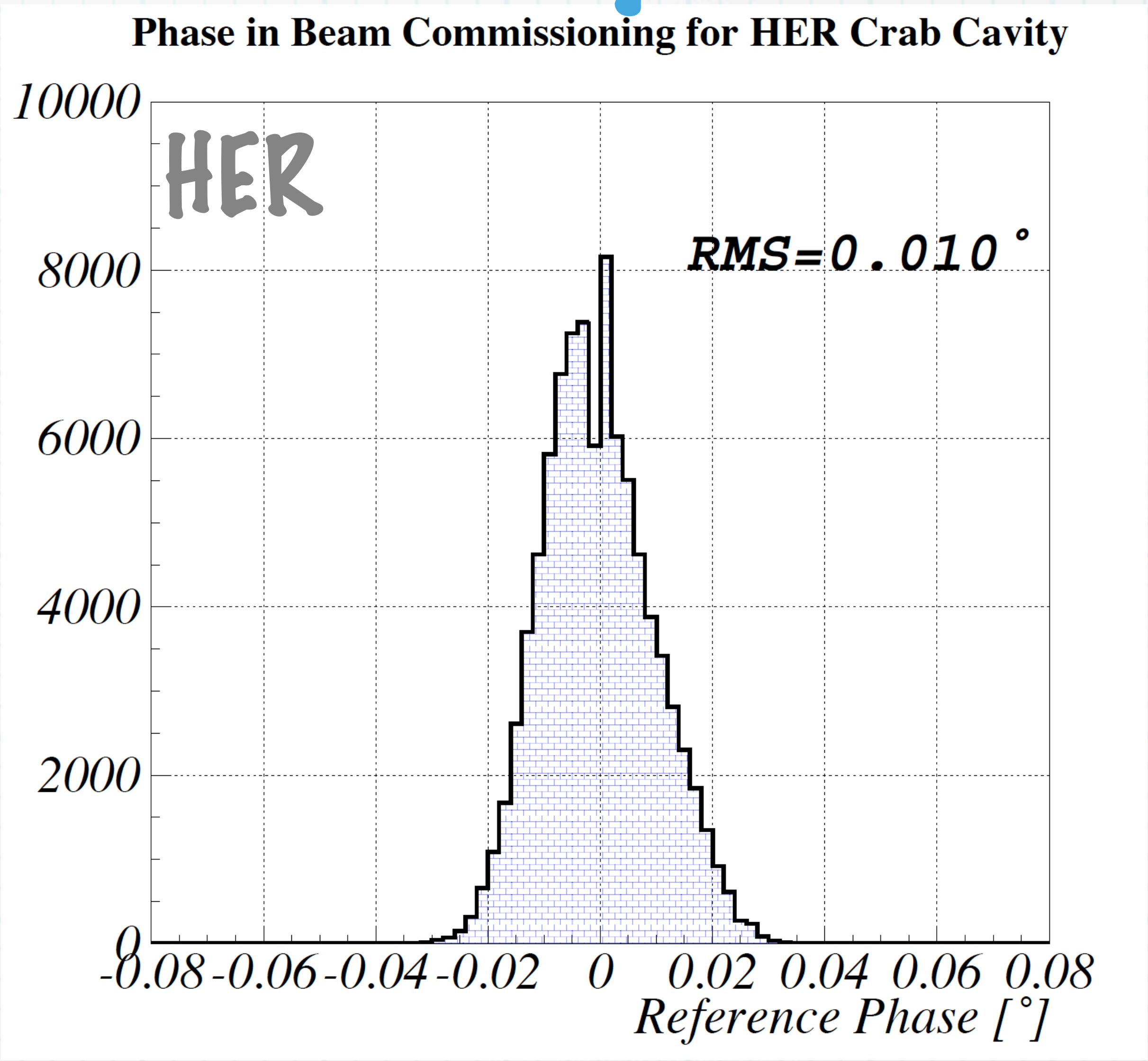
Crab Cavity & Coaxial Coupler in Cryomodule

K. Hosoyama et al



RF Phase Stability



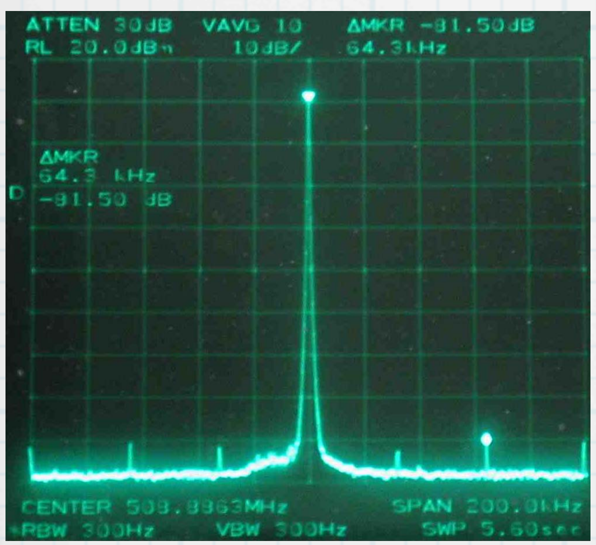


* Phase stability of the crab mode was better than the requirement with the rf feedback.
* Slow stability below 1 Hz is shown above.
* Independent measurement by a spectrum analyzer shows better than 0.01 deg for f > 2 kHz, 0.1 deg for 2 Hz < f < 2 kHz.
* Backlash or friction exists in the coaxial tuner for the LER.

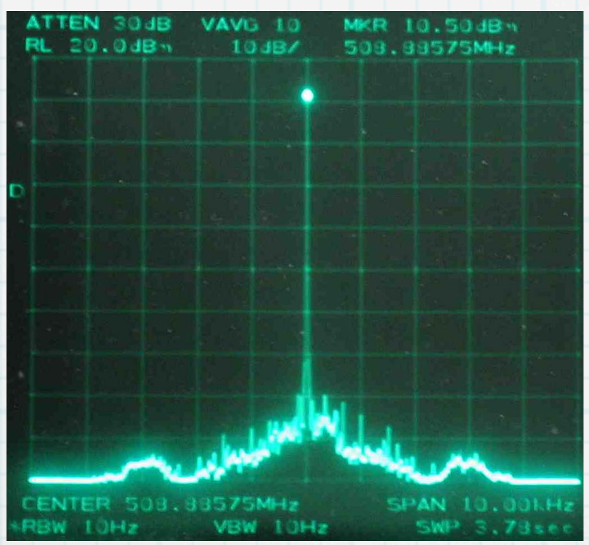
Phase stability

- Spectrum of pick up signal is consistent with phase detector data.
- Phase fluctuation faster than 1 kHz is less than ±0.01°, and slow fluctuation from ten to several hundreds of hertz 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.

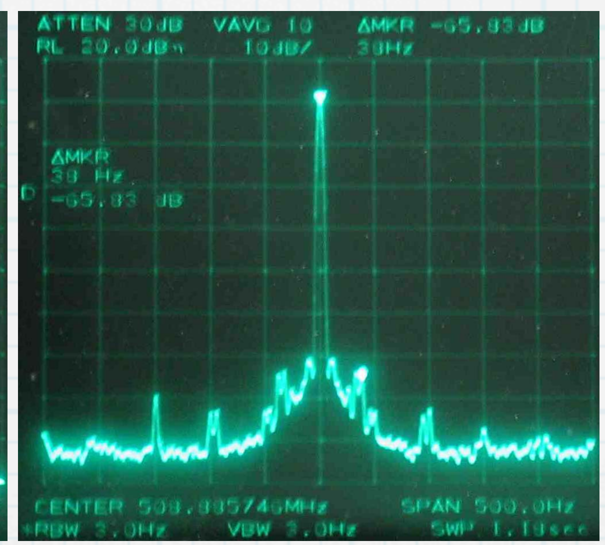
According to b-b simulation by Ohmi-san, allowed phase error for N-turn correlation is $0.1\times\sqrt{N}$ (degree).



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

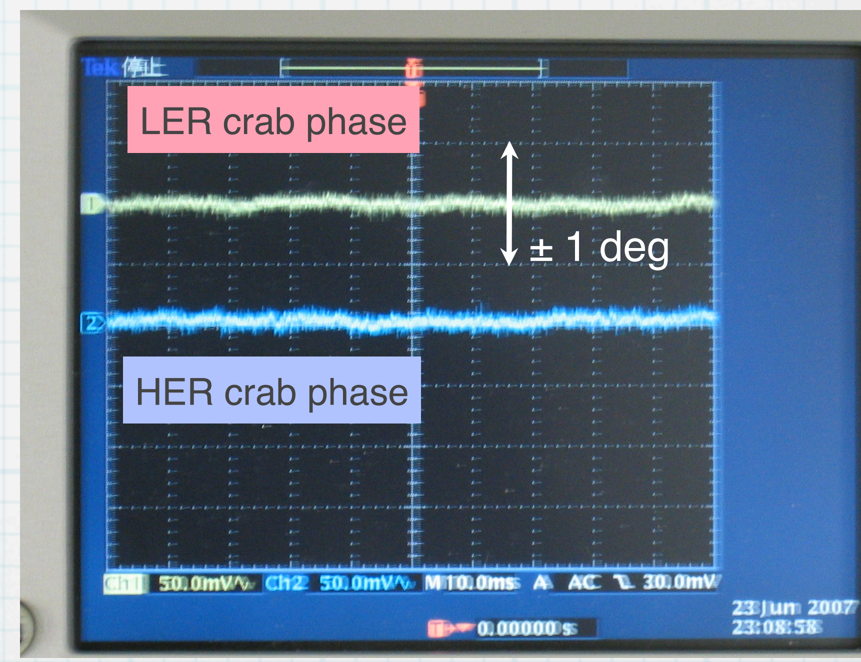


Span 10 kHz



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

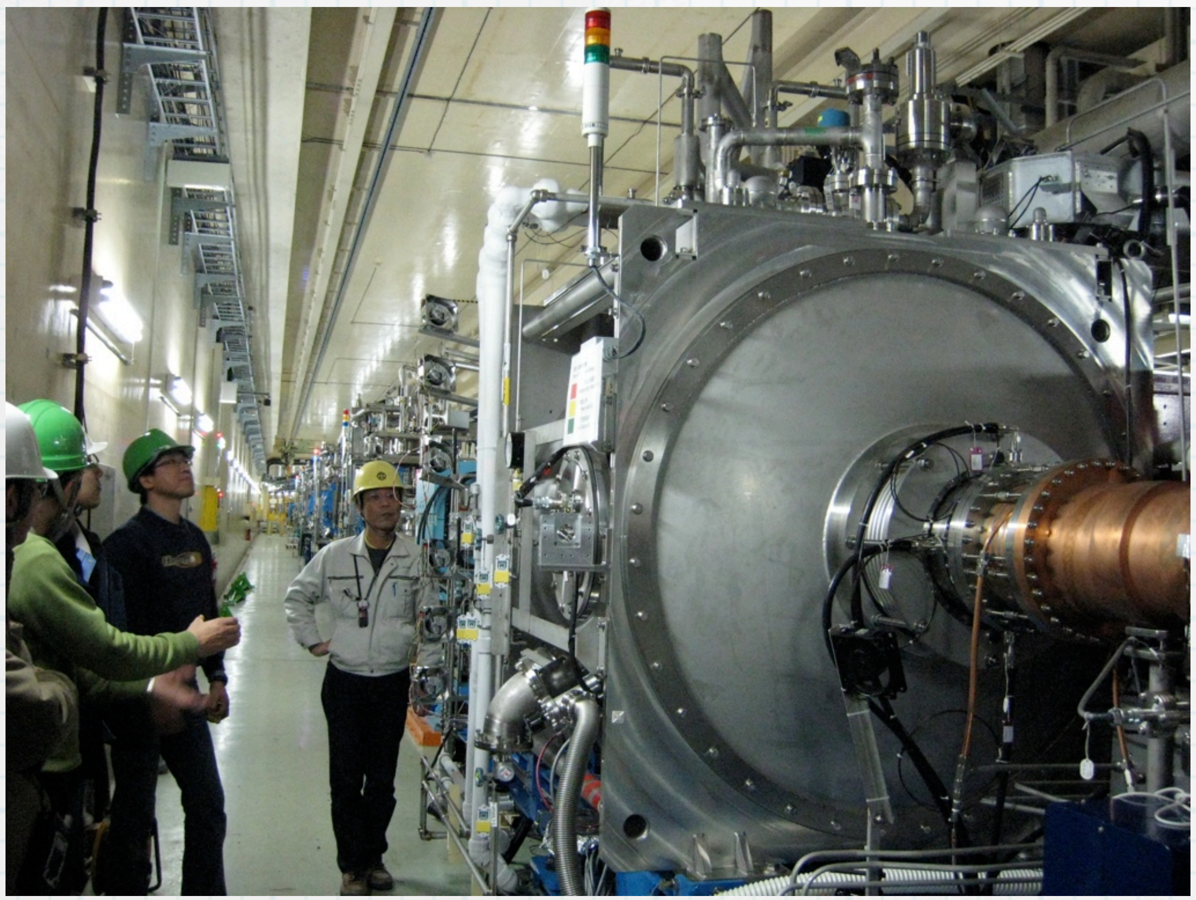
Spectrum around the crabbing mode measured at a pick up port of the LER crab cavity. Beam current was between 450 and 600 mA.



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

K. Akai

Finally two crab cavity was installed in KEKB, one for each ring in January 2007.



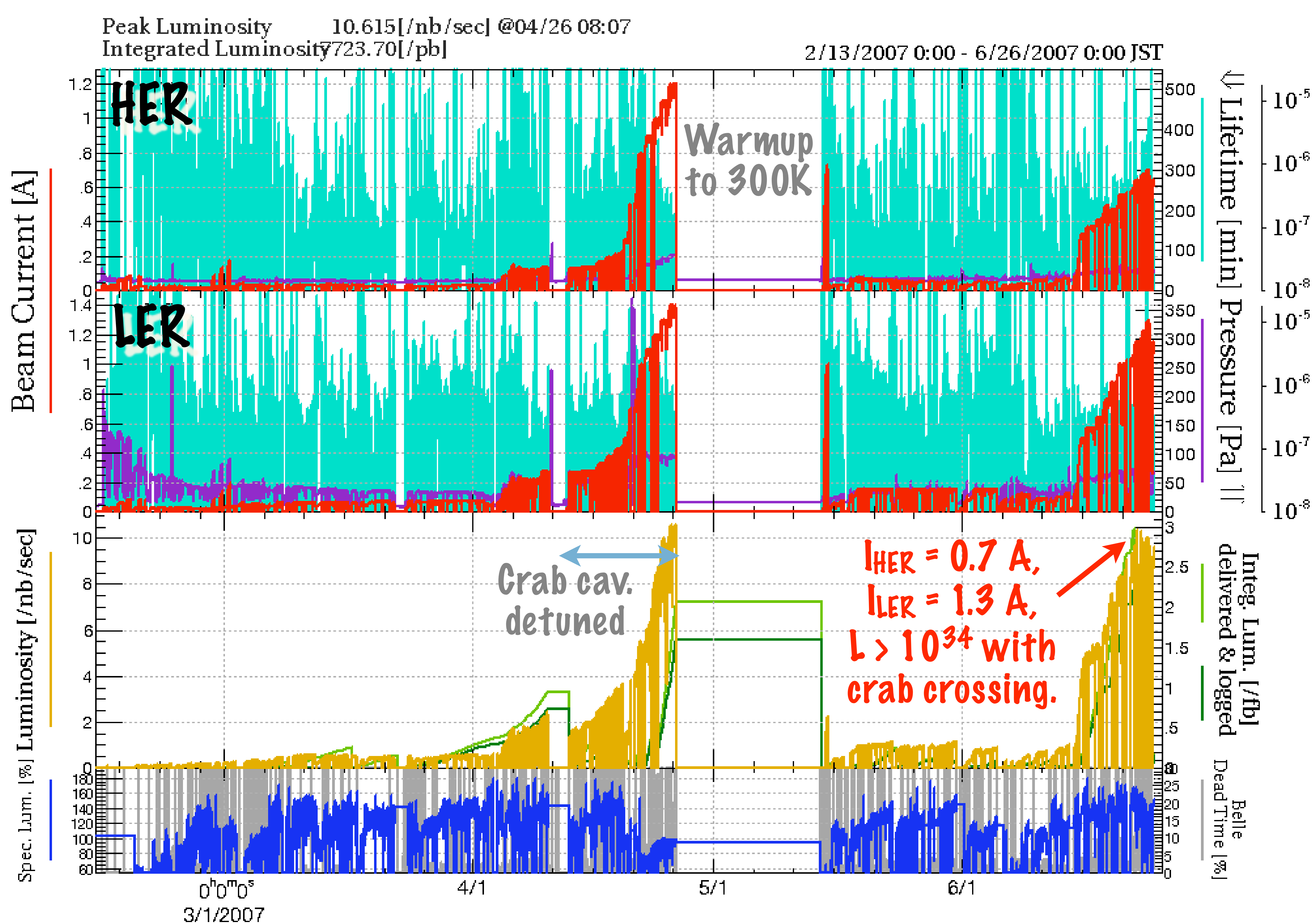
HER (e-, 8 GeV)

LER (e+, 3.5 GeV)

Crab Crossing Started at KEKB

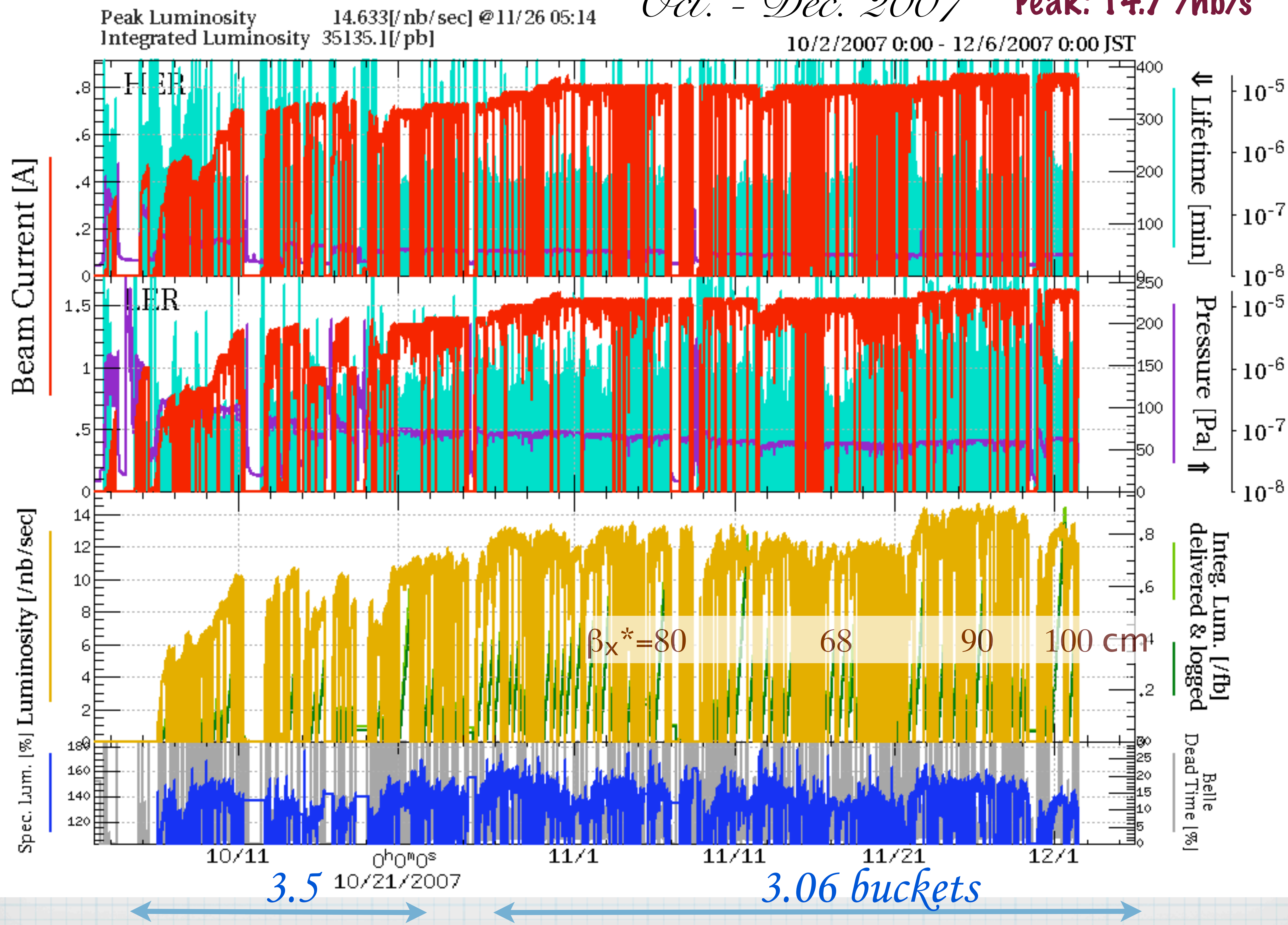
First time in the world!

- A number of checks have confirmed the effective head-on collision:
  - streak camera
  - crab-phase scan
  - sign change and scan of crab voltage
  - horizontal beam-beam kick
  - vertical crabbing
- The highest vertical beam-beam tune-shift parameter is about 0.088 so far, which is higher than the geometrical gain due to head-on by 15%.
- Due to the low-current operation with longer bunch spacing (98 ns), the effect from electron cloud has been negligible.
- There are a few issues are speculated for the reason why the luminosity is lower than the prediction, but not yet confirmed.



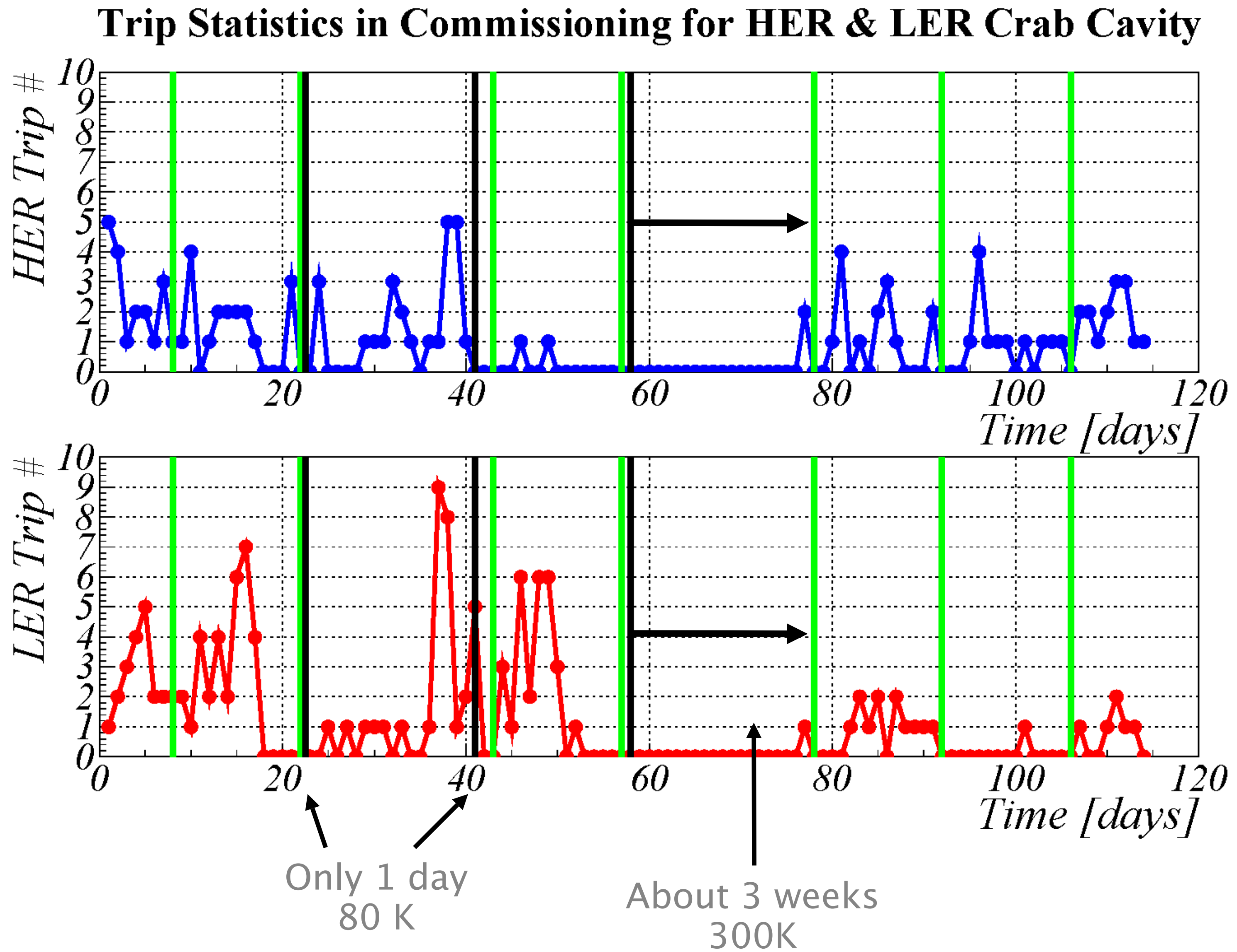
Peak Luminosity 10.615[/nb/sec] @04/26 08:07
Integrated Luminosity 7723.70[/pb]
2/13/2007 0:00 - 6/26/2007 0:00 JST
HER
LER
Warmup to 300K
Beam Current [A]
Lifetime [min]
Pressure [Pa]
Crab cav. detuned
I_{HER} = 0.7 A,
I_{LER} = 1.3 A,
$L > 10^{34}$ with crab crossing.
Luminosity [/nb/sec]
Integ. Lum. [/fb] delivered & logged
Spec. Lum. [%]
Belle Dead Time [%]
$0^h0^m0^s$
3/1/2007
4/1
5/1
6/1

Oct. - Dec. 2007 **Peak: 14.7 /nb/s**



Number of trips per cavity per ring.

From March/1 to June/22 (114days)



Green line shows the maintenance day.
Black line shows the warm-up period.

Trip Statistics

	LER	HER
March	58	43
April	55	21
May	13	16
June	7	27
Total	133	107

Y. Yamamoto

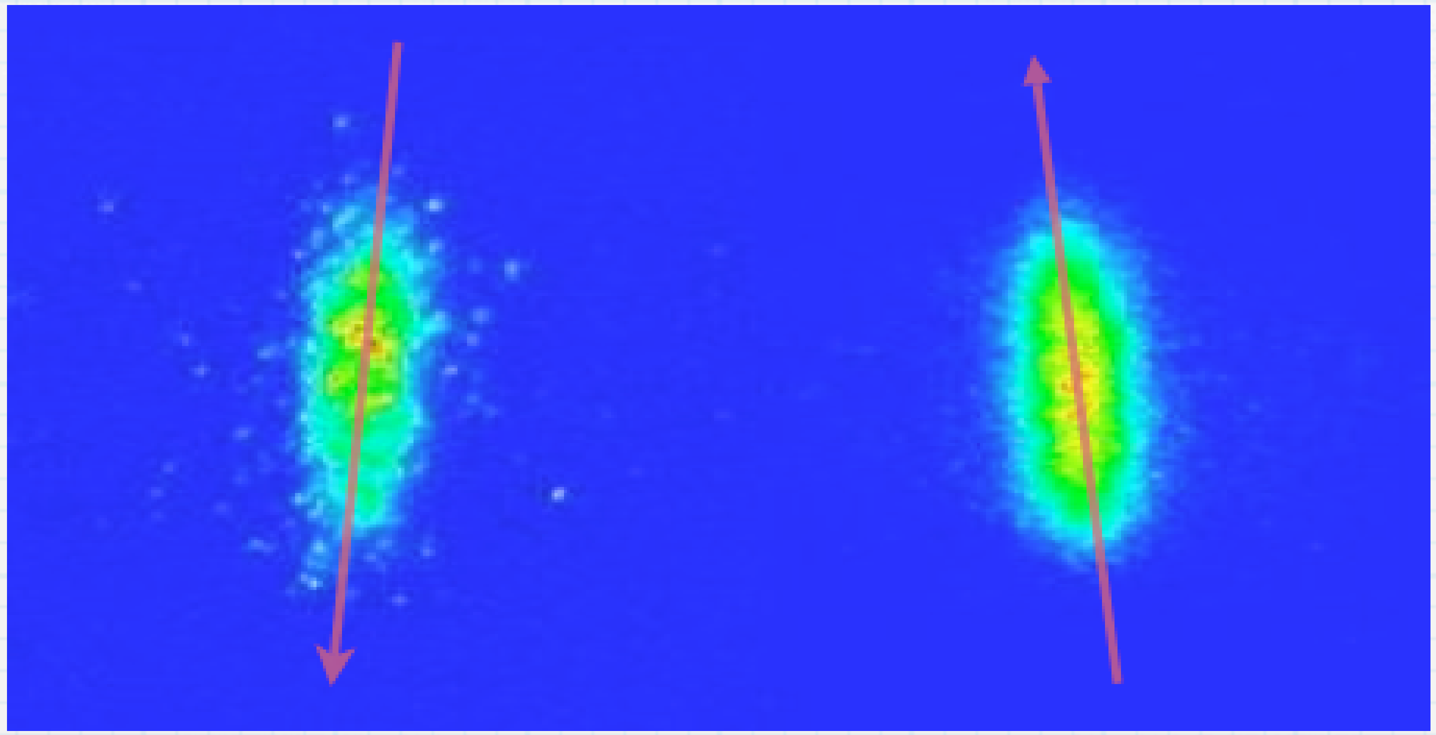
Beams has indeed tilted!

- Observation with Streak Cameras (H. Ikeda et al, FRPMN035)

inside of
the rings

outside of
the rings

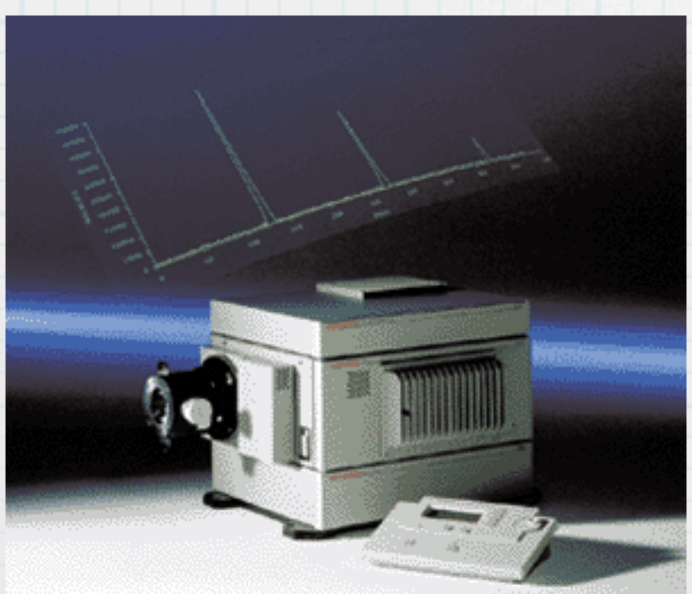
longitudinal



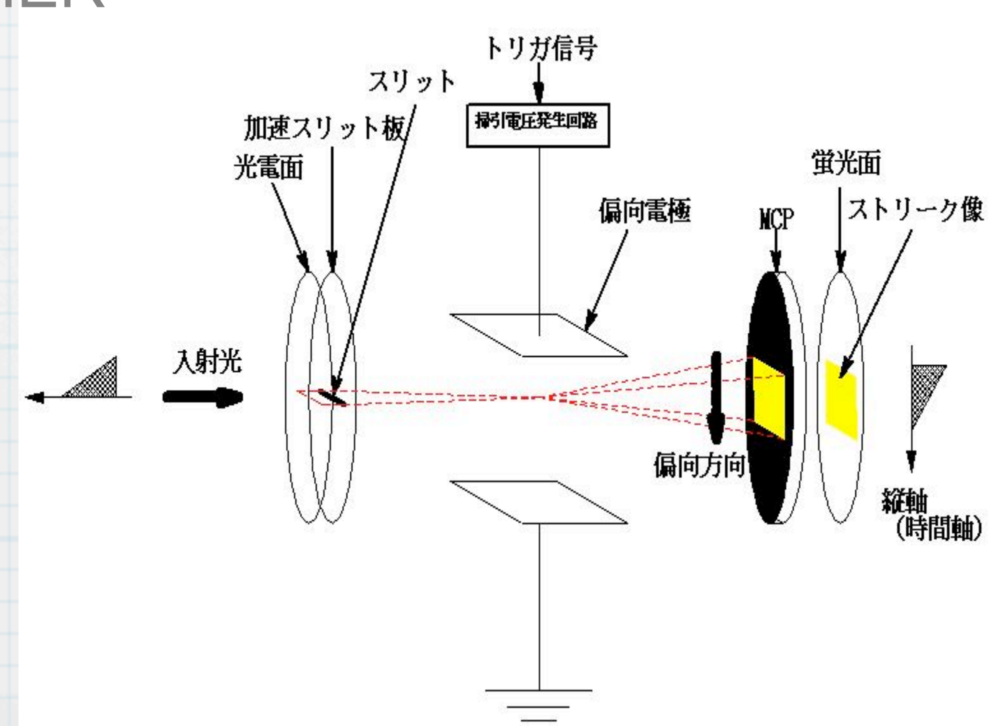
LER

HER

horizontal

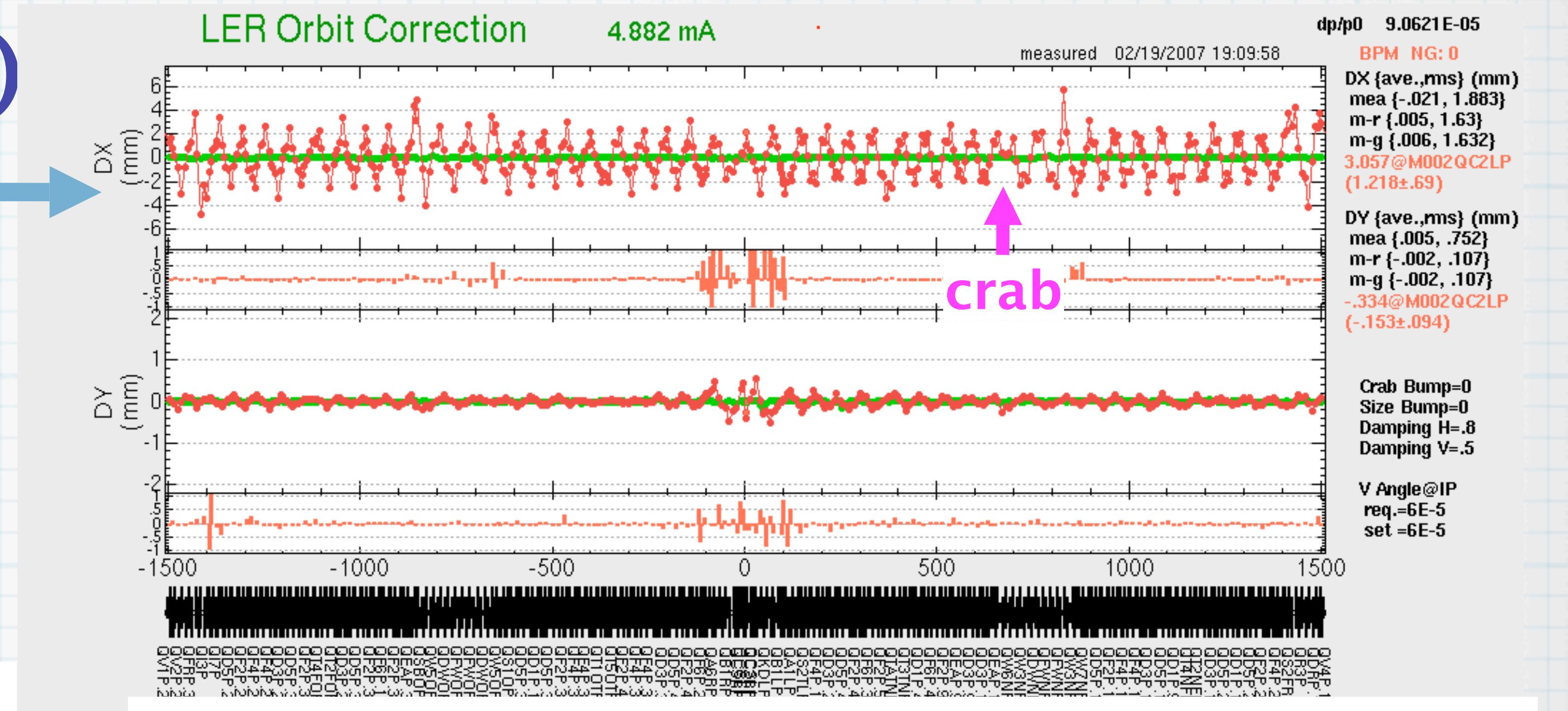


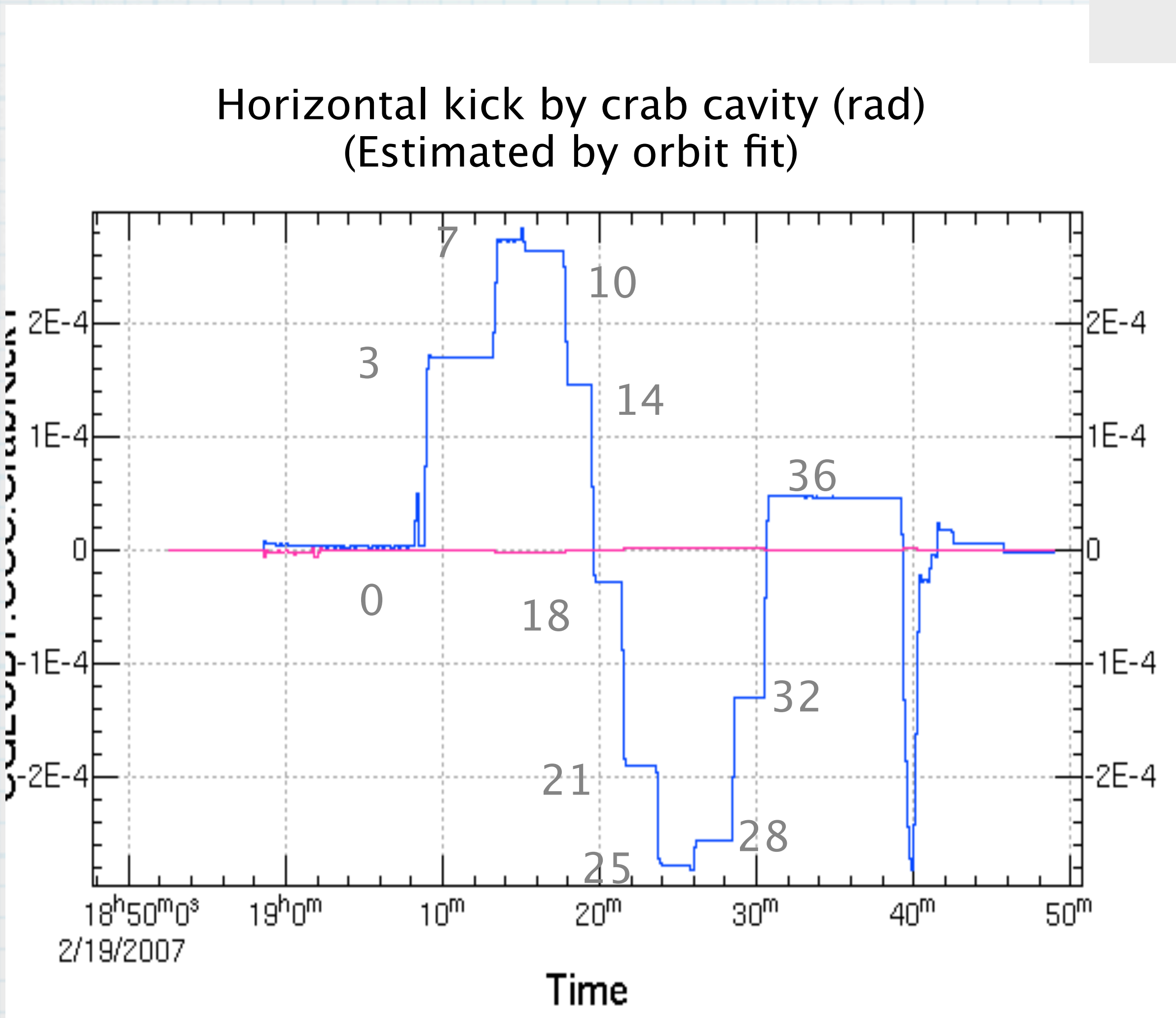
The streak camera

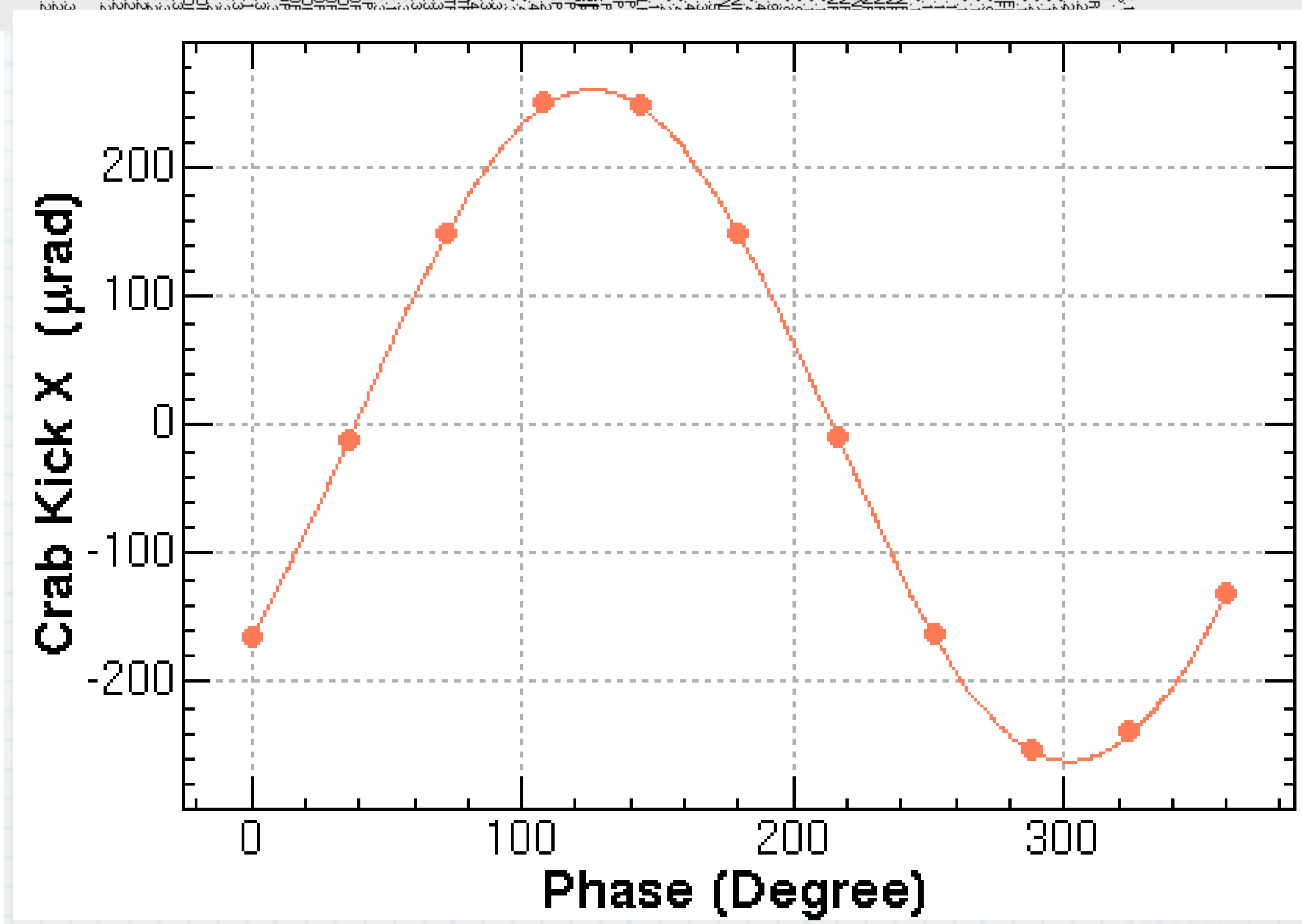


Crab Phase Scan (LER)

Horizontal orbit by crab kick





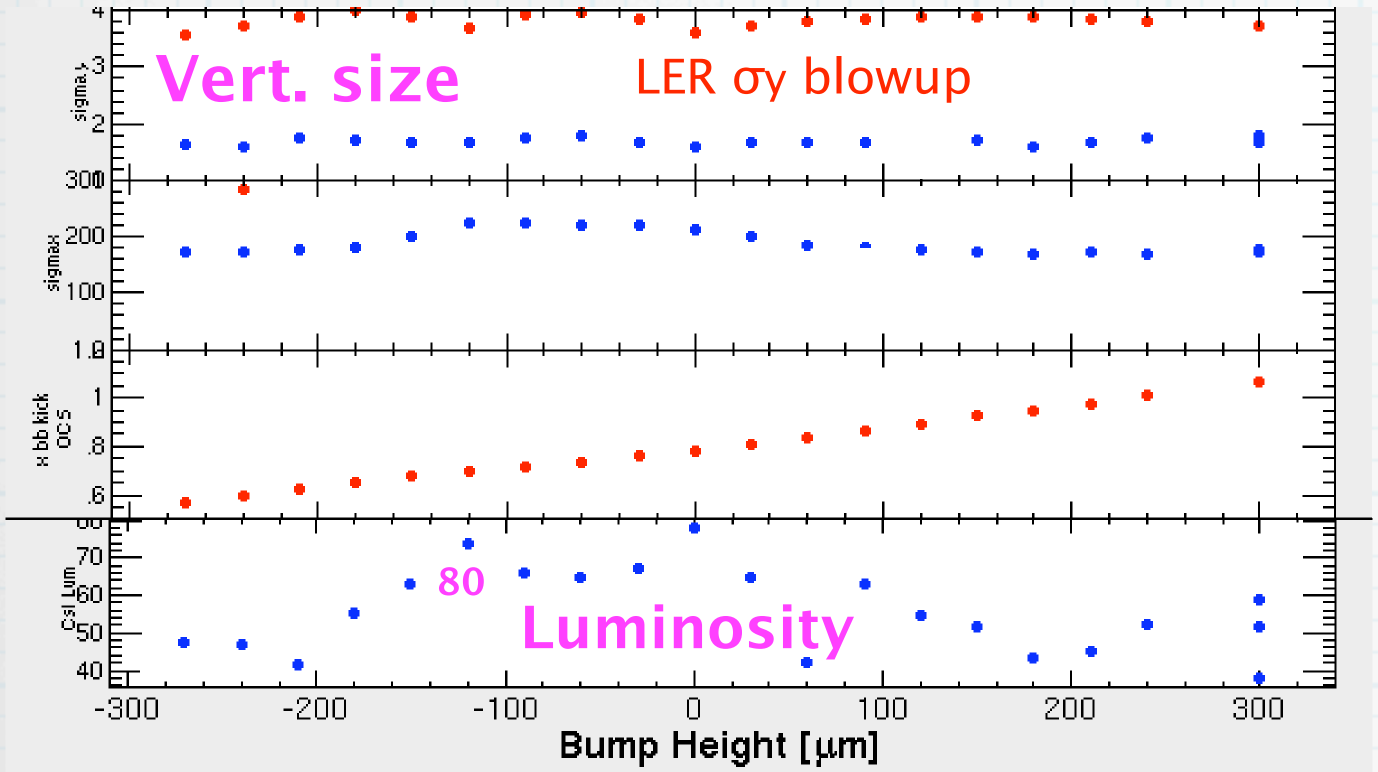


V_{crab} set:1.0MV, estimated: 0.987MV

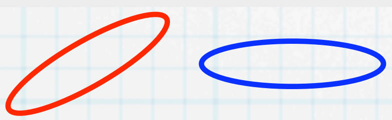
agree to each other very well.

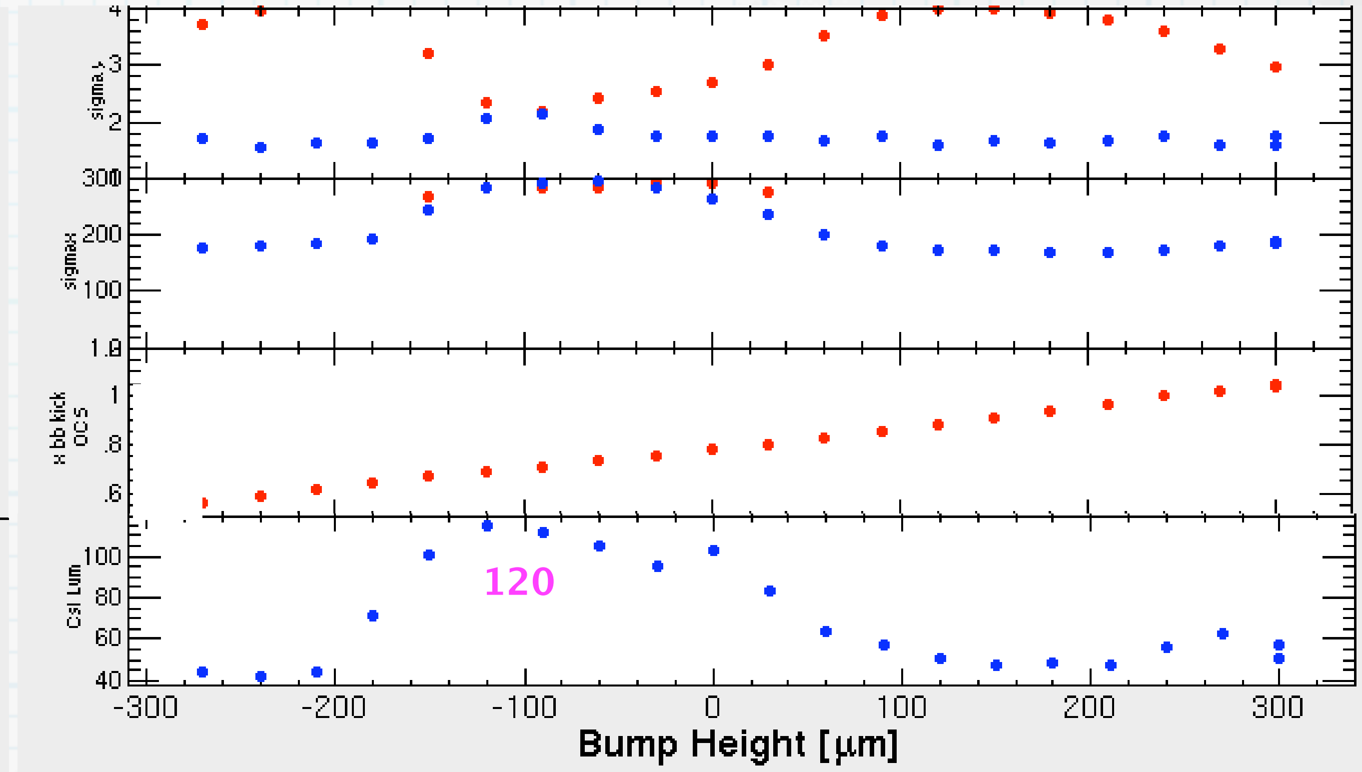
Sign Change in the Crab Angle

H. Koiso

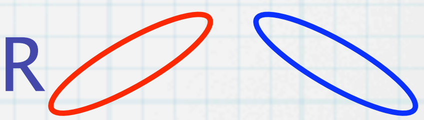


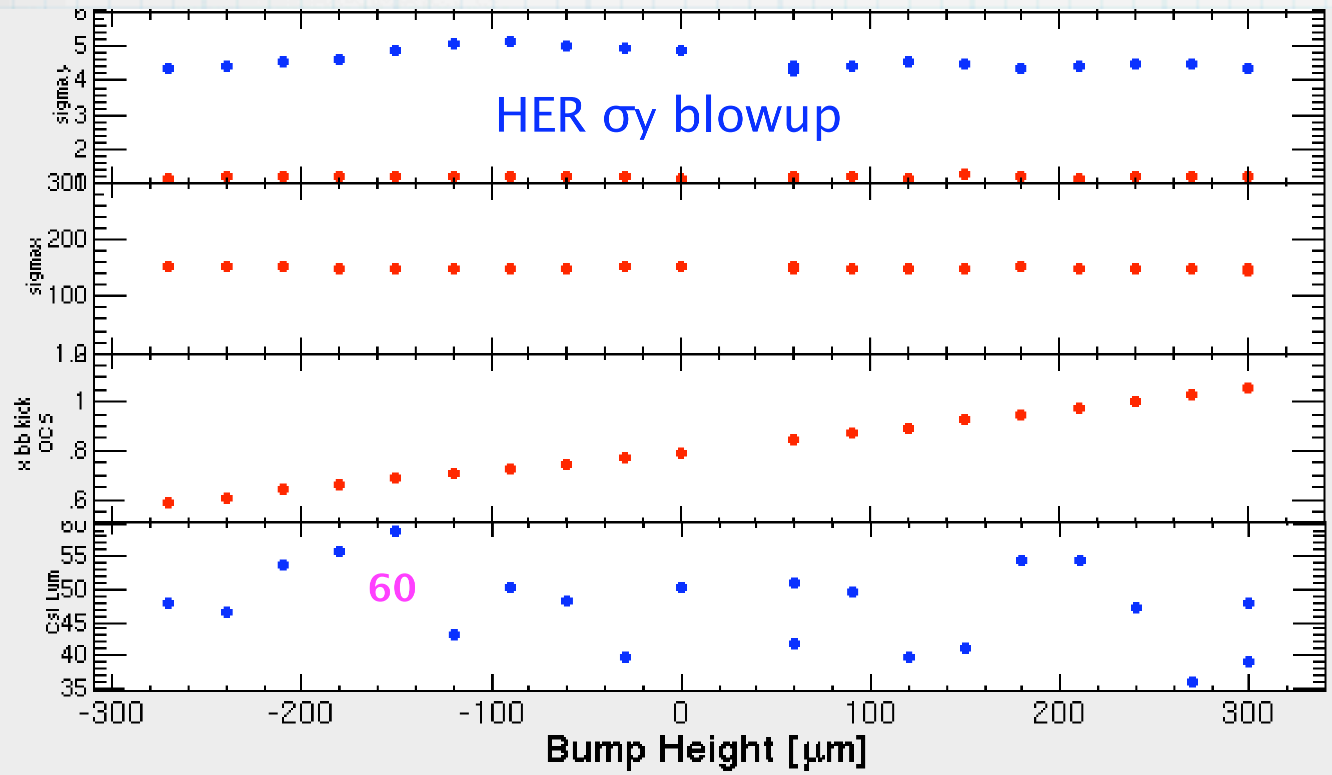
Reversed LER crab angle



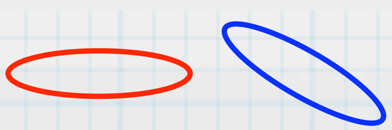


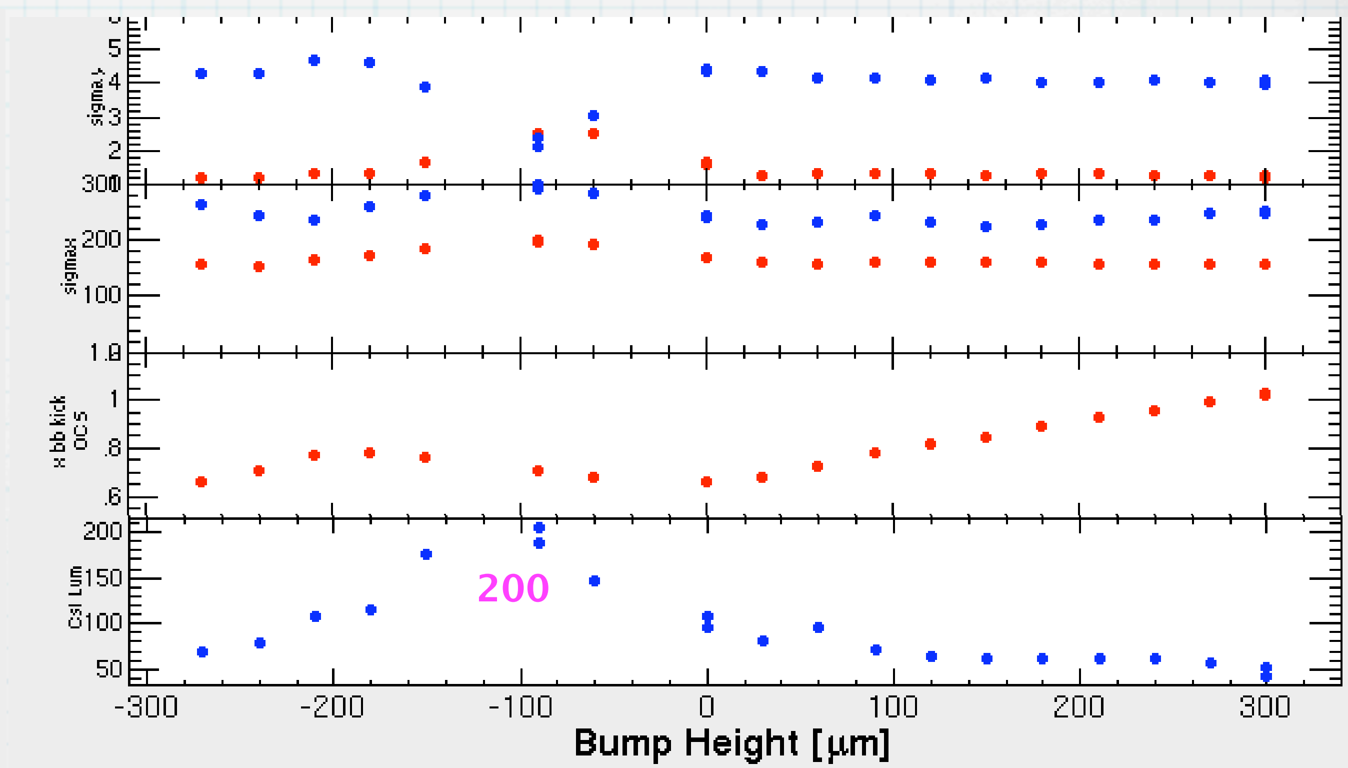
Reversed LER & HER



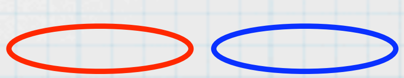


Reversed HER



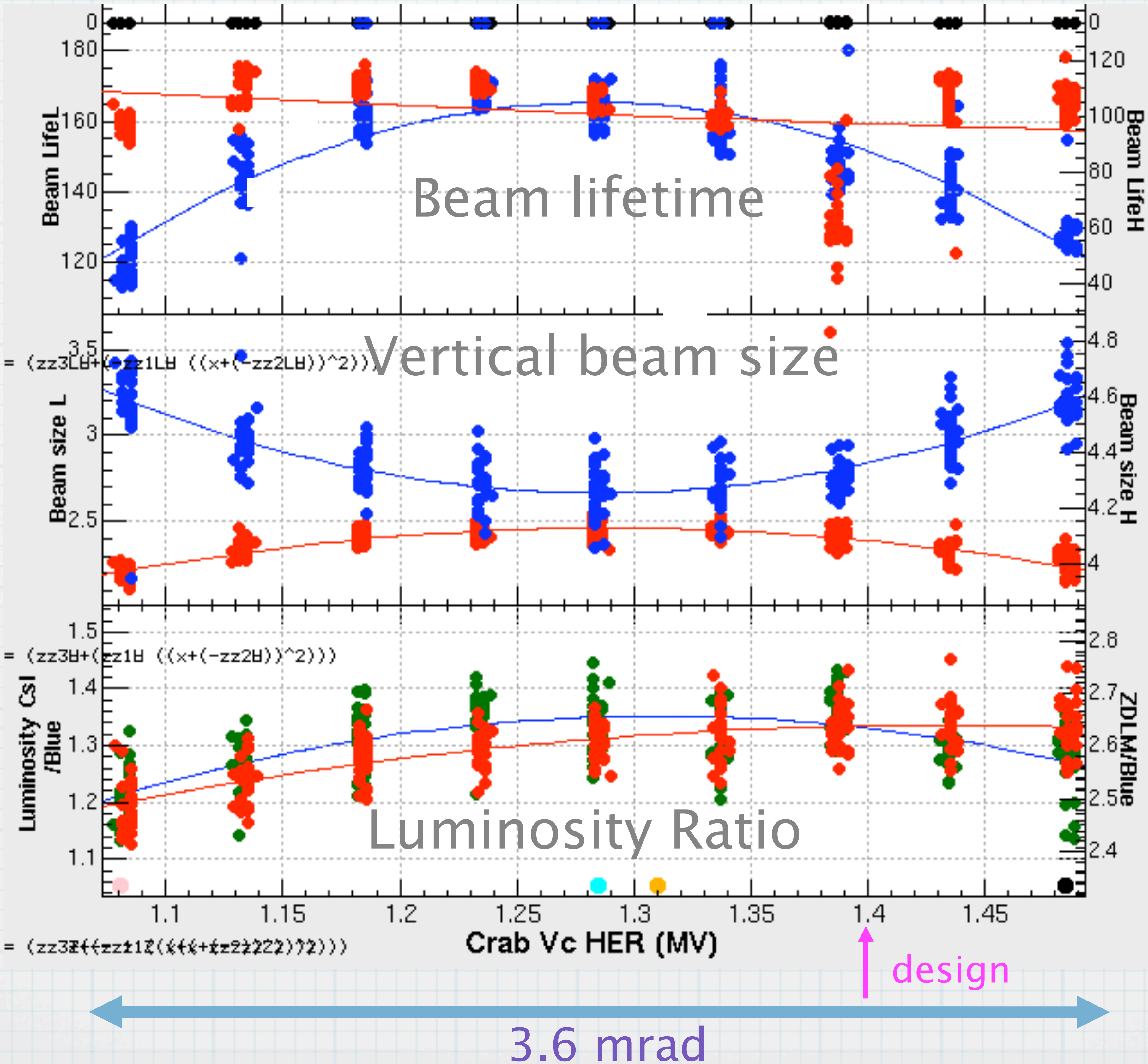


Both correct



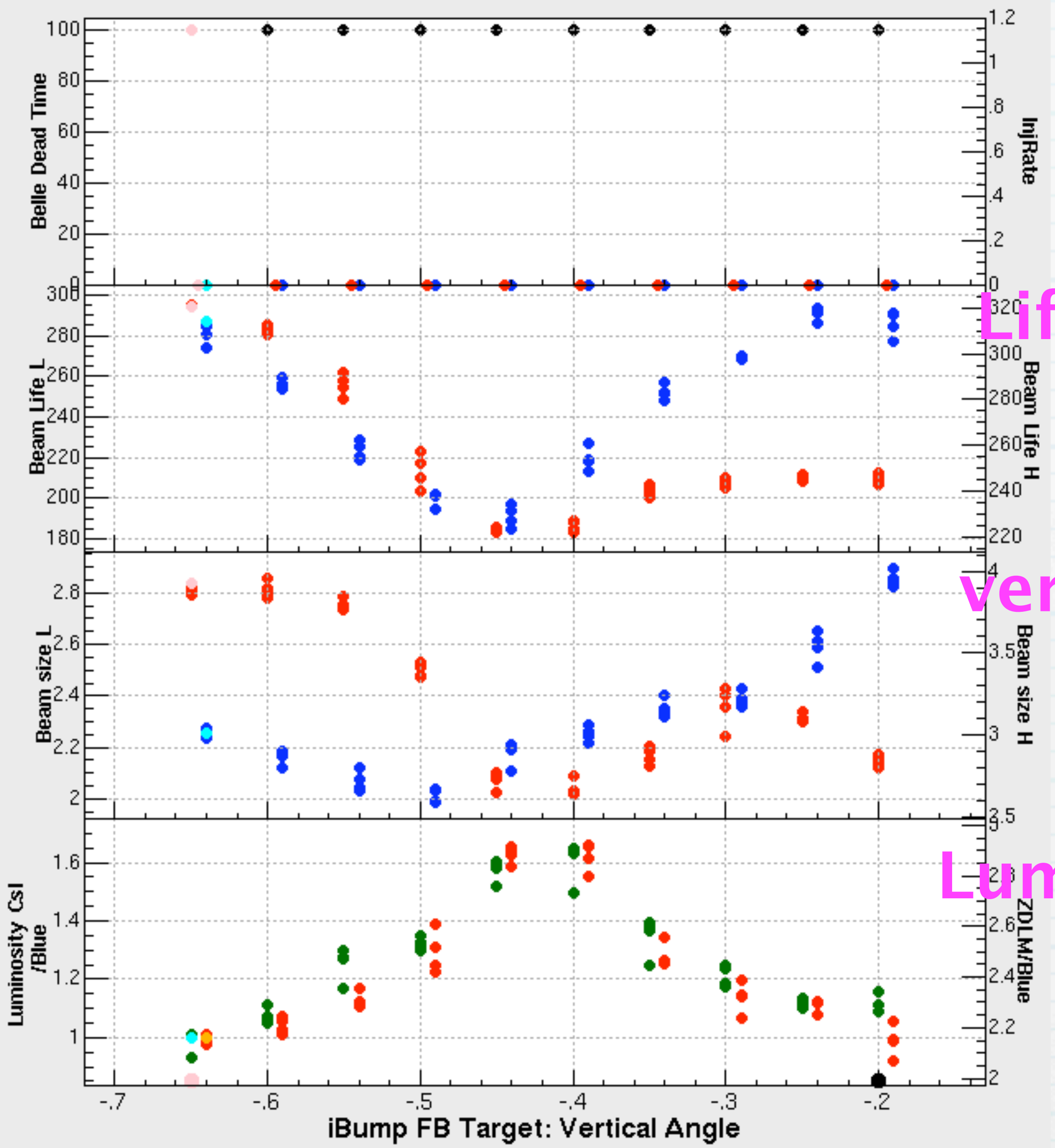
V_{crab} Scan (HER)

H. Koiso

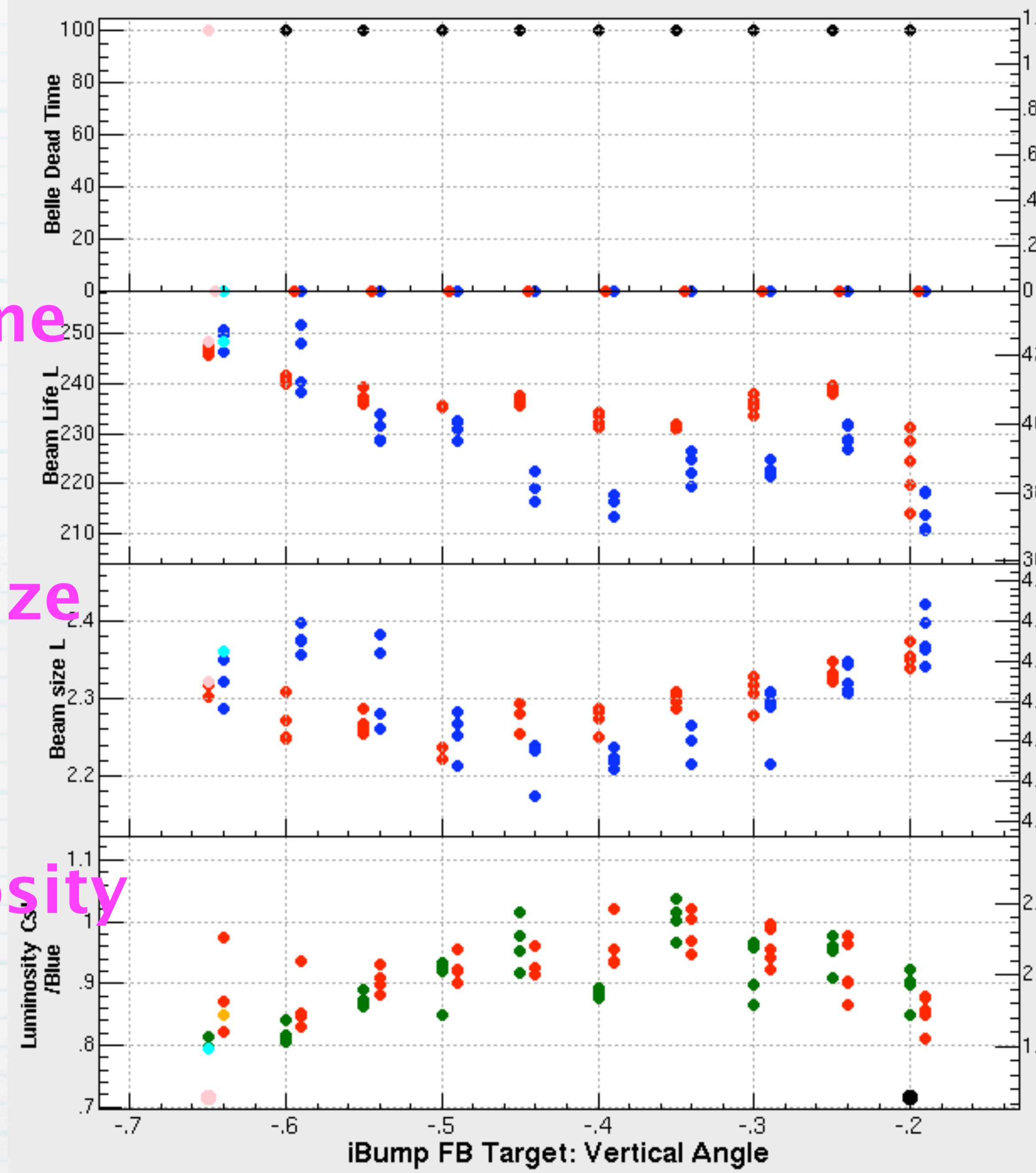


Vertical Crabbing ?

H. Koiso



asymmetric



more symmetric

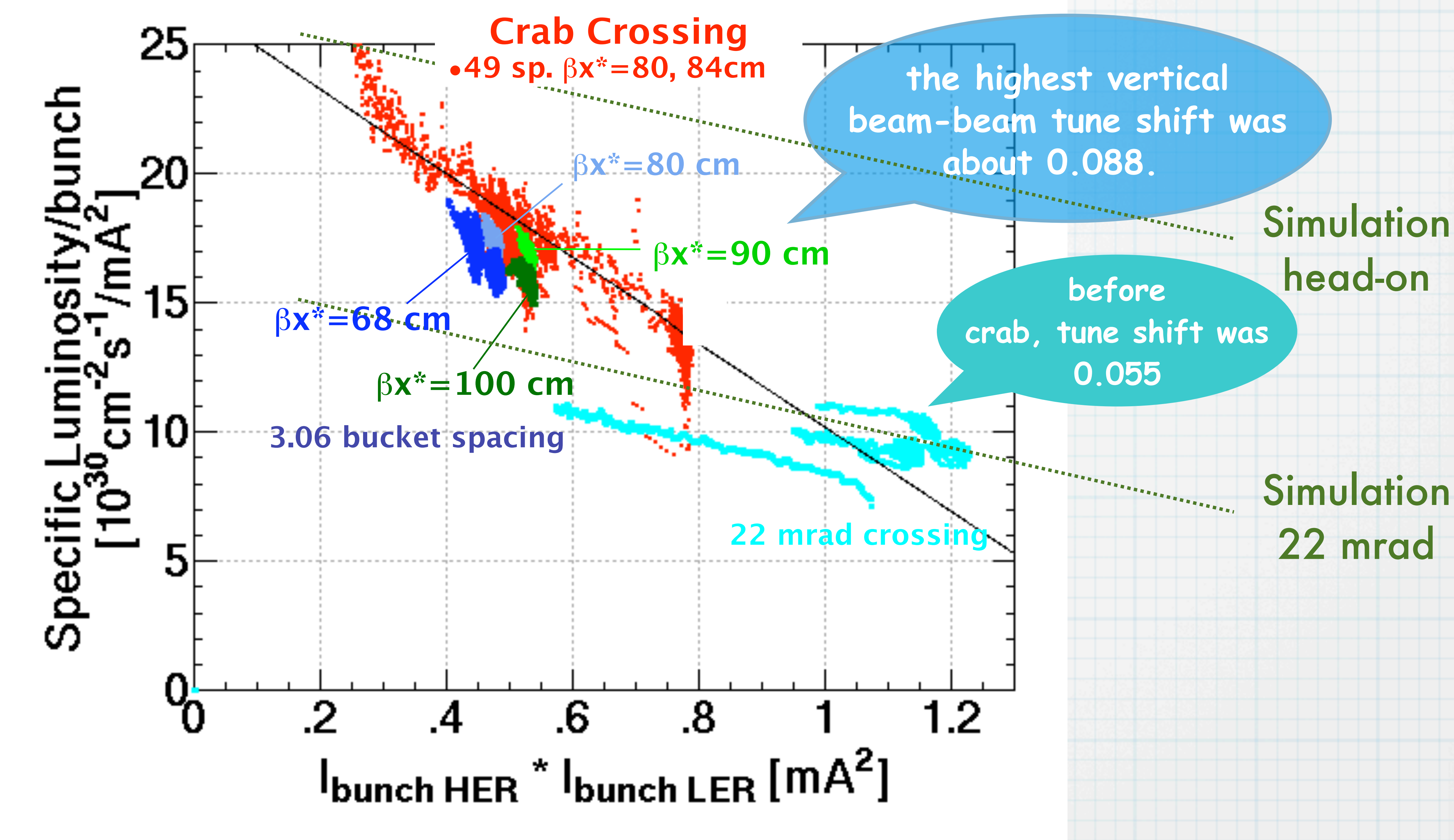
Lifetime

vert. size

Luminosity

Vertical size dependence on the vertical crossing angle should be symmetric around the vertical head-on collision.

Specific Luminosity



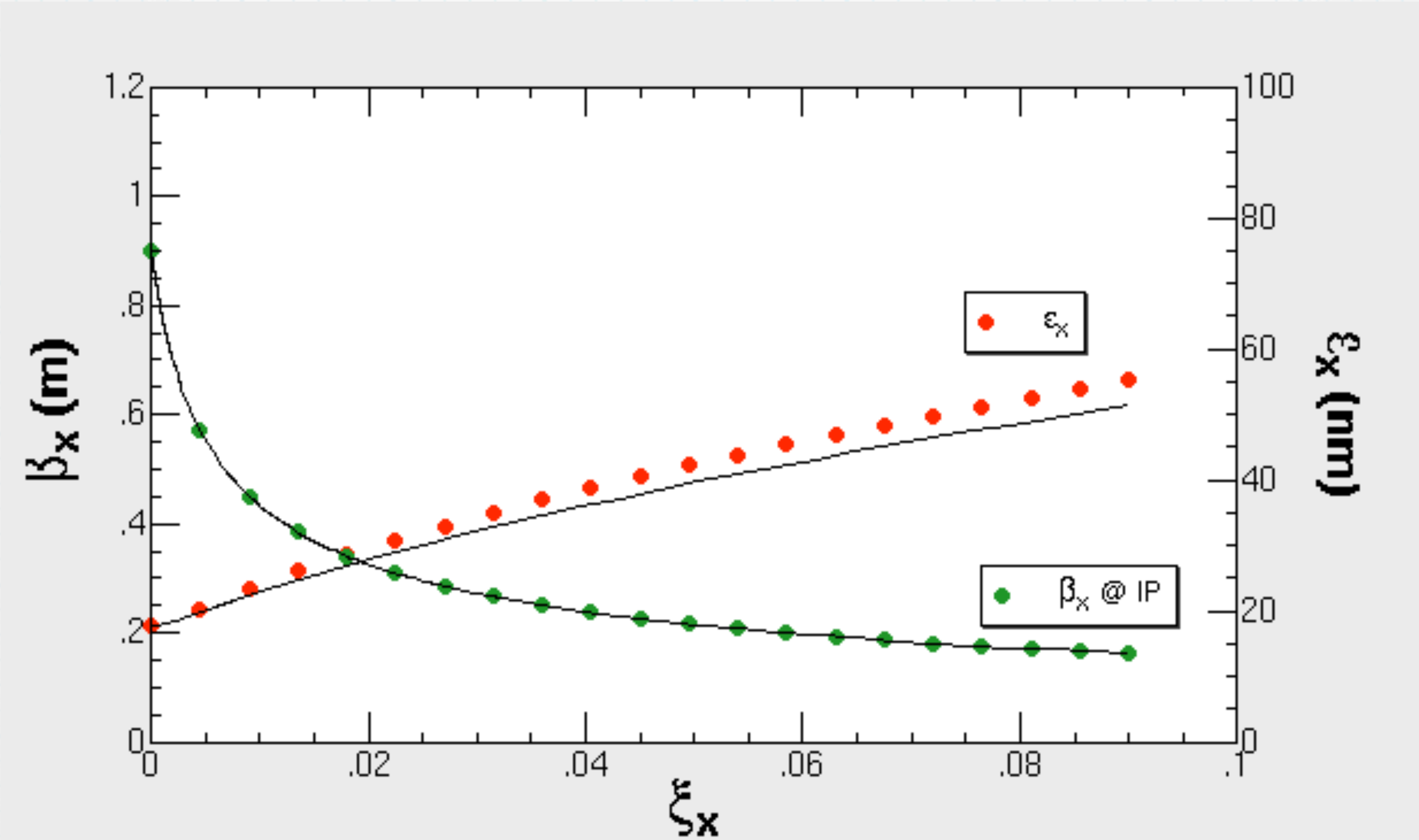
- A number of measurements indicate effective head-on collision.
- The vertical tune shift became higher than 0.088. Before crab, it was 0.055.
- The specific luminosity / bunch was improved more than the geometrical gain.
- Need more time to achieve the goal (X2 specific luminosity).

Why the specific luminosity drops faster than expected?

Speculations:

* Lifetime may be limited by the dynamic- β and dynamic emittance caused by bea-beam.
* Electron Cloud in the LER: Luminosity becomes better for longer bunch spacing.
* The SPOOABS nature in the optimum condition of the collision: Too many parameters.
* Synchrotron-betatron resonance near 1/2 integer.
* .. and more ..

LER dynamic-β and emittance

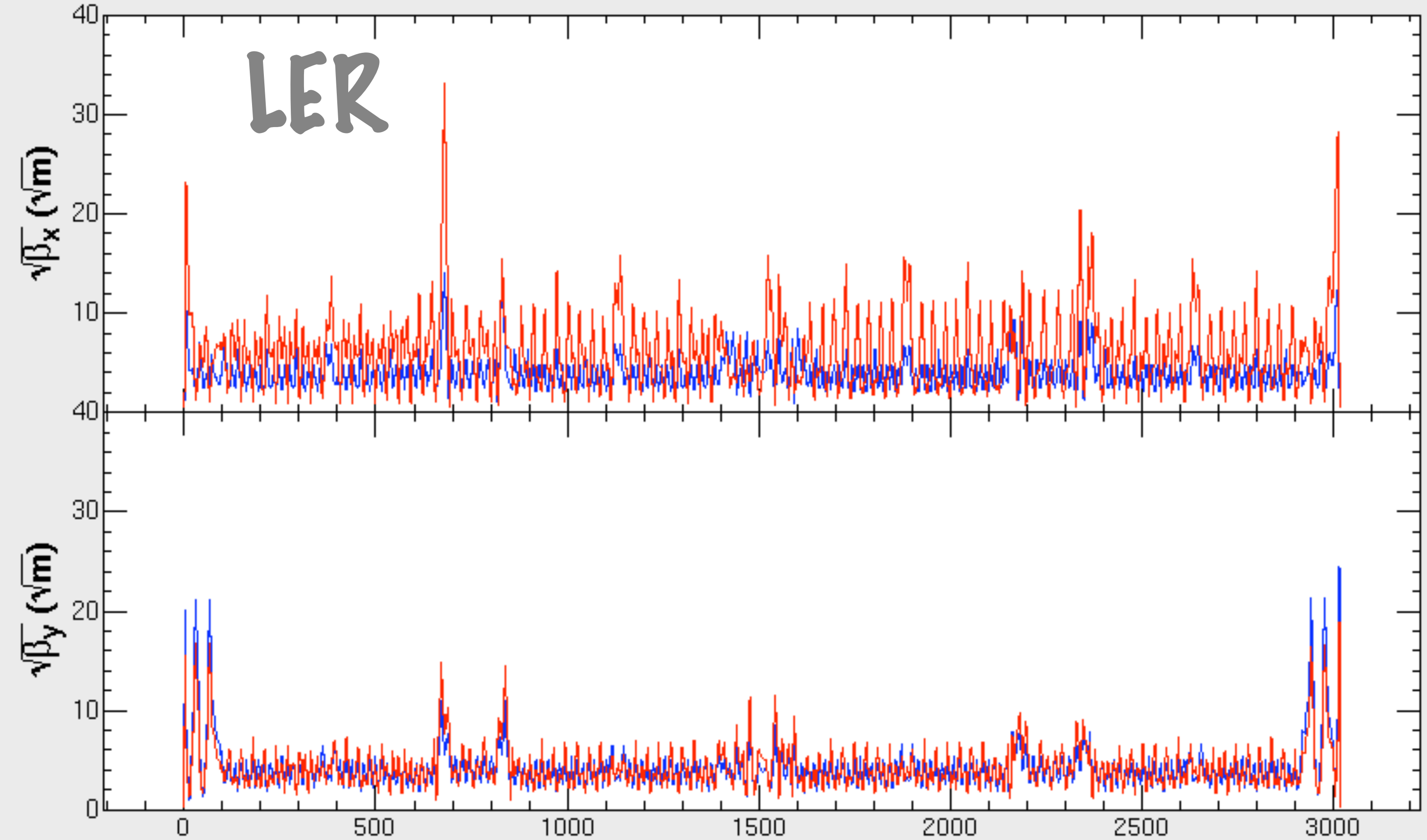


LER	
ν_x	45.506
ν_y	43.57
β_x [m]	.9
β_y [m]	.0059
ξ_x max	.09
ξ_y max	.1

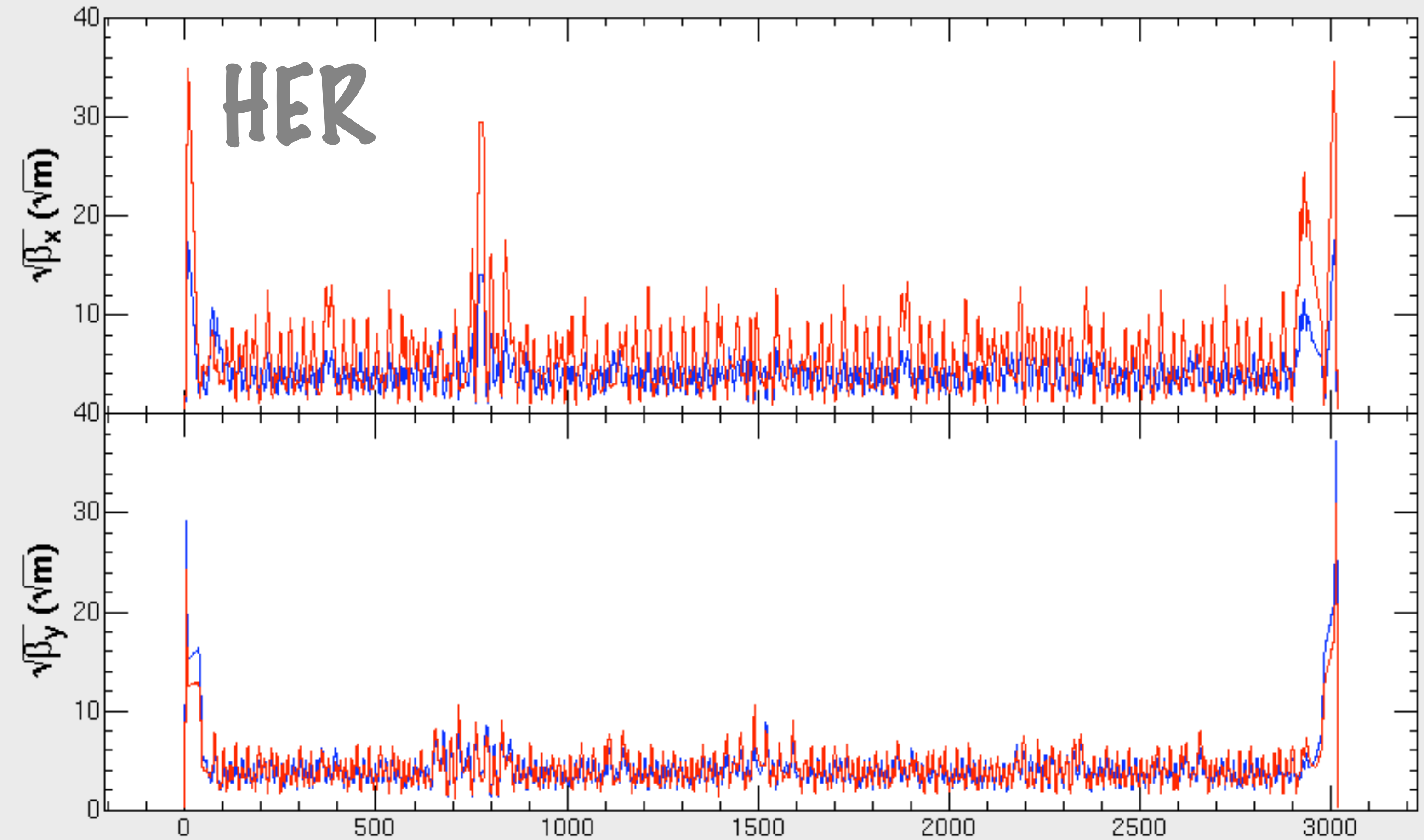
The focusing force of the beam-beam interaction not only squeezes the beam at the interaction point, but increases the emittance drastically.

Y. Funakoshi

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

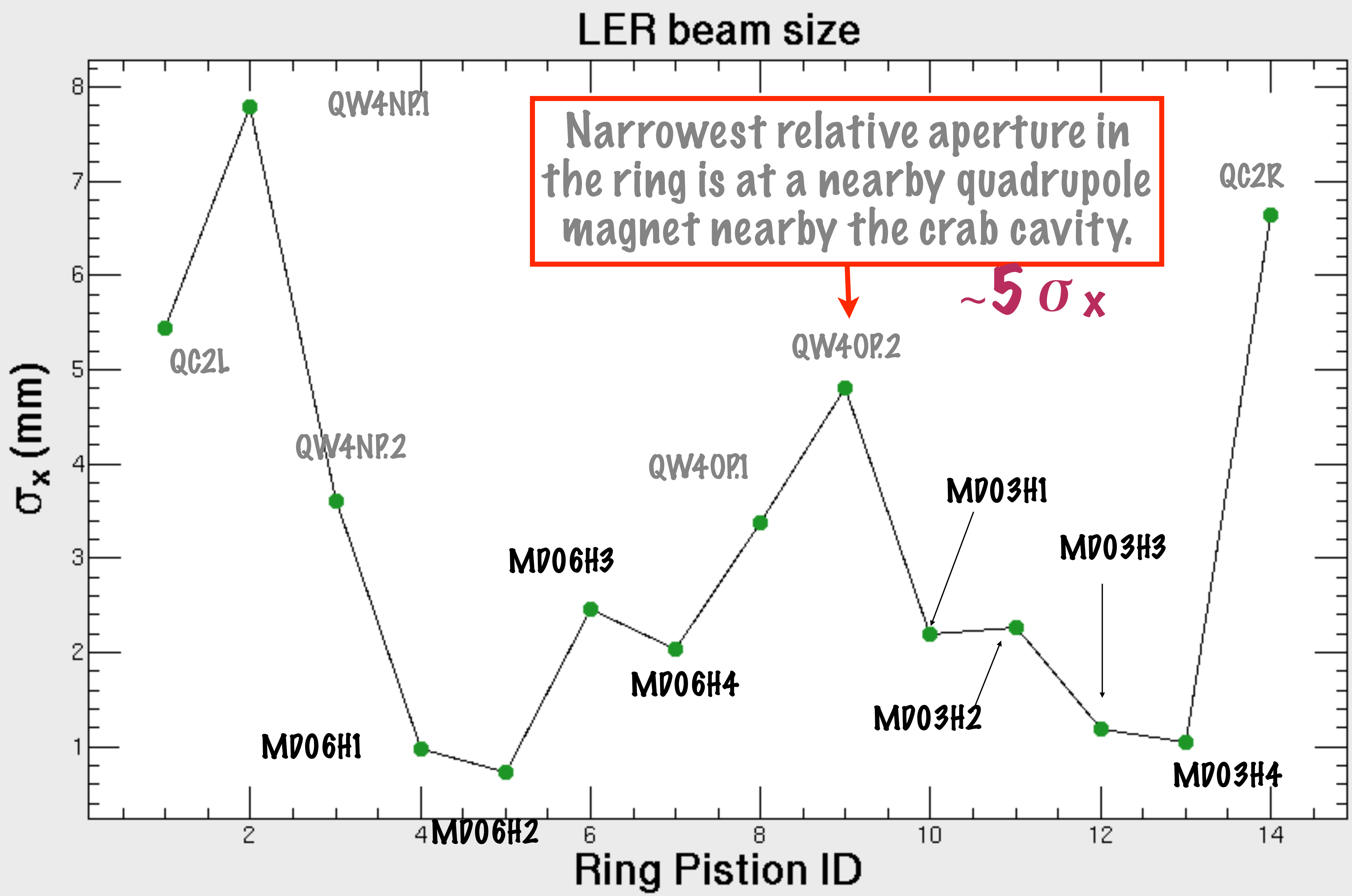


with/without beam-beam effects



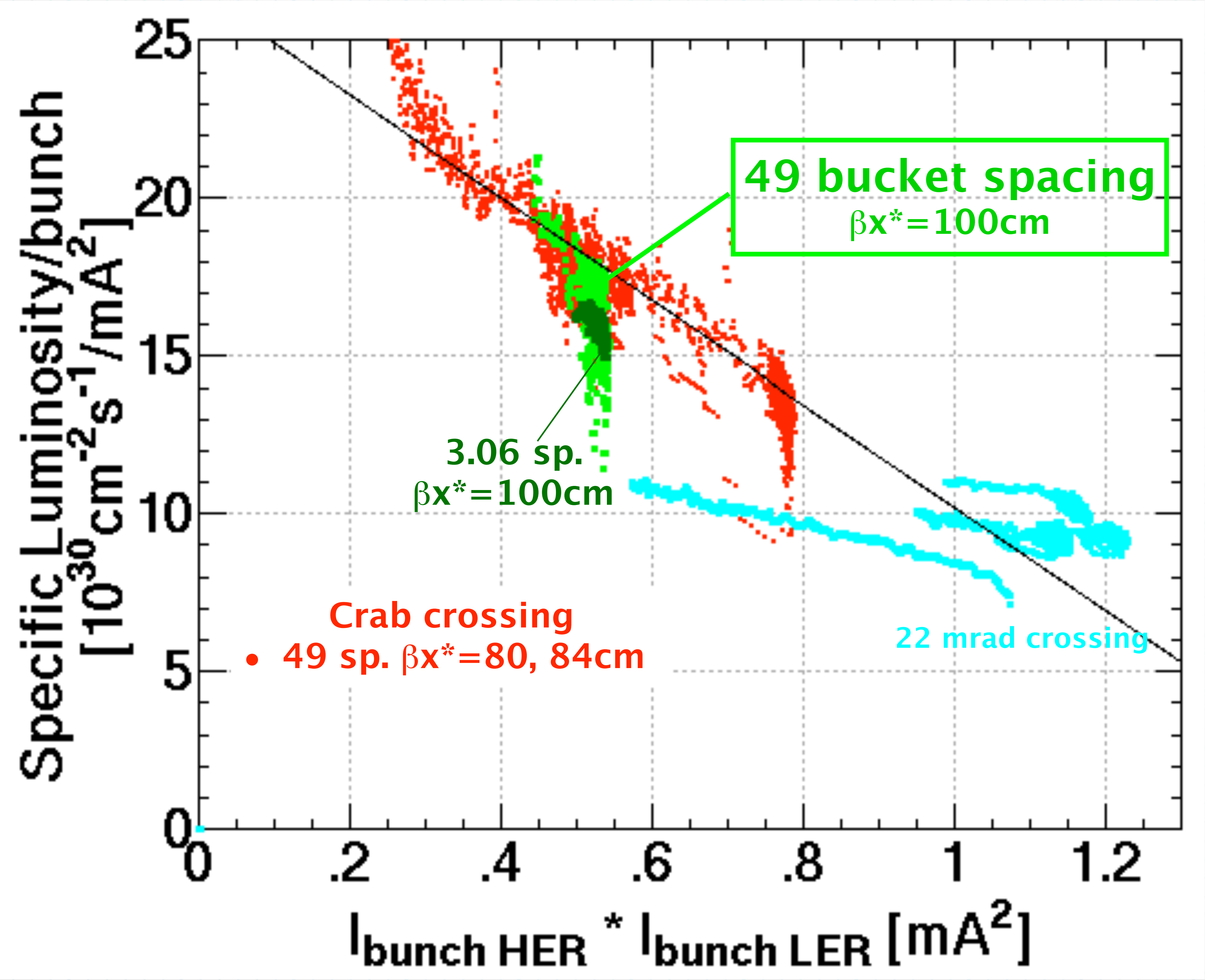
Y. Funakoshi

The lifetime may be limited by the dynamic beta effect.



Y. Funakoshi

Specific Luminosity becomes better for longer bucket spacing. Due to e-cloud?



Too many tuning knobs?

Table 3: Tuning knobs for the crab crossing and their observables. Many depend only on the beam size σ_y at the synchrotron radiation monitor (SRM), besides the luminosity $\mathcal{L}$.

Knob	Observable	frequency: every	
Relative beam offset IP	Beam-beam kick measured by BPMs around the IP	1 sec	2
Relative beam angle IP	BPMs around the IP	1 sec	2
Global closed orbit	All $\sim$ 450 BPMs	15 sec	-
Beam offset at crab cavities[11]	BPMs around the crab cavity	1 sec	2
Betatron tunes	tunes of non-colliding pilot bunches	$\sim$ 20 sec	4
Relative rf phase	center of gravity of the vertex	10 min.	1
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	1
Rf phase of crab cavity	hor. kick vs. crab voltage response	$\sim$ 7 days	2
Vertical waist position	$\mathcal{L}$ and σ_y at the SRM	$\sim$1 day	2
Local x-y couplings and dispersions at IP	$\mathcal{L}$ and σ_y at the SRM	$\sim$1 day each	16
Sextupole settings	$\mathcal{L}$ and lifetime	$\sim$ 3 days	106
X-y coupling parameter at the crab cavities	$\mathcal{L}$ and σ_y at the SRM	$\sim$ 3 days	4
Crab kick voltage	$\mathcal{L}$ and σ_y at the SRM	$\sim$ 7 days	2

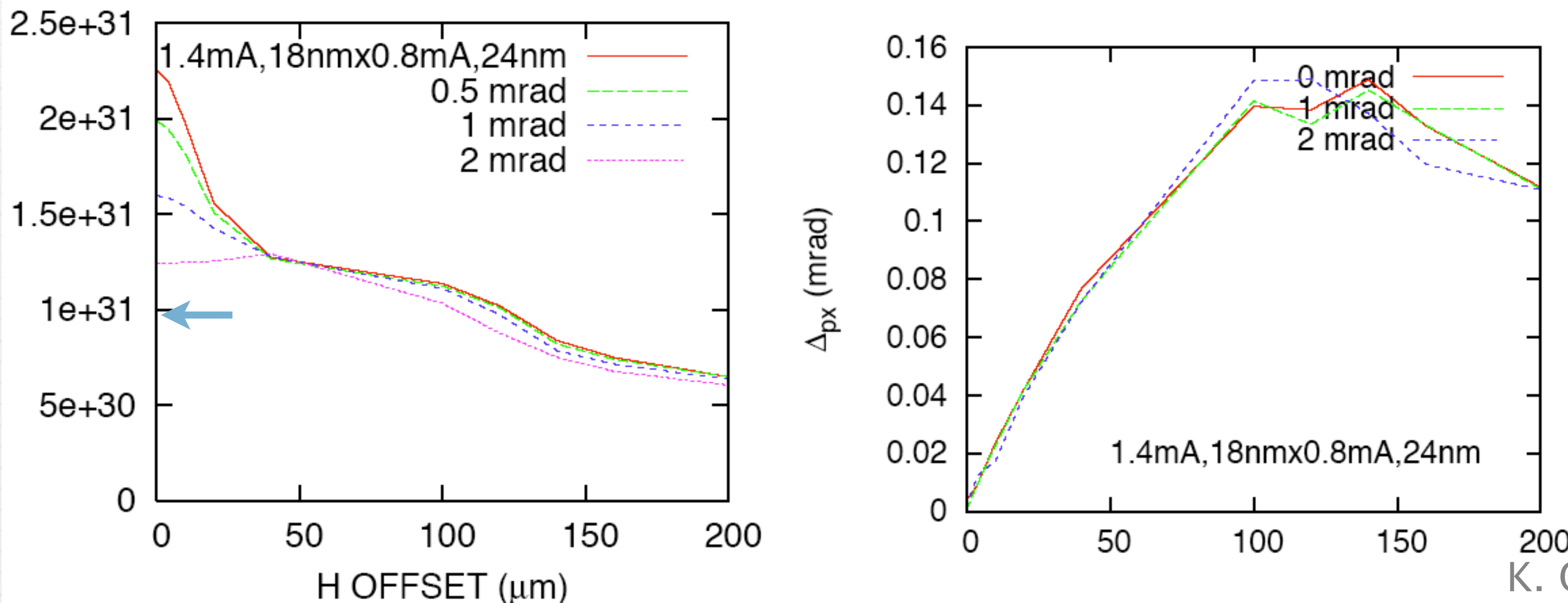
- **Many knobs are determined by scans only on the luminosity, beam sizes, and the lifetime.**
- **Scan is slow, each takes about 30 minutes.**
- **Question in the multi-dimensional nonlinear optimization.**

sharply-peaked-optimum-on-a-broad- shoulder (SPOOABS)

An example: the Horizontal Offset and the crossing angle at the IP

- Luminosity

beam-beam kick



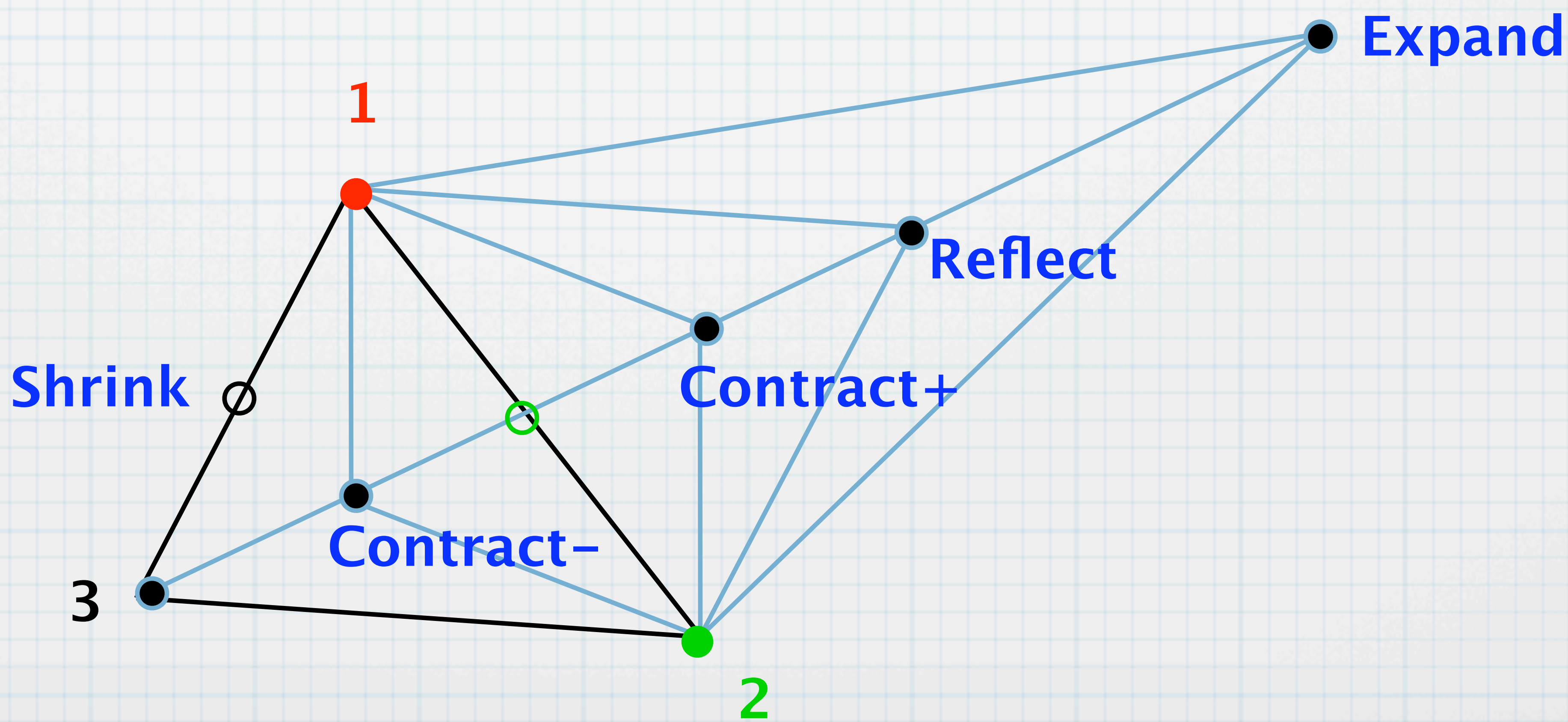
K. Ohmi

- Luminosity degrades by a small error in any one of the collision parameters. The horizontal offset of two beams and the crossing angle at the IP are such an example.
- Horizontal offset must be much less than 25 μm, and the crossing angle less than 1.5 mrad to see the effect of crab crossing.
- There are more than 20 of such parameters. If one of them is largely off, the optima of other parameters cannot be found.

Downhill simplex method

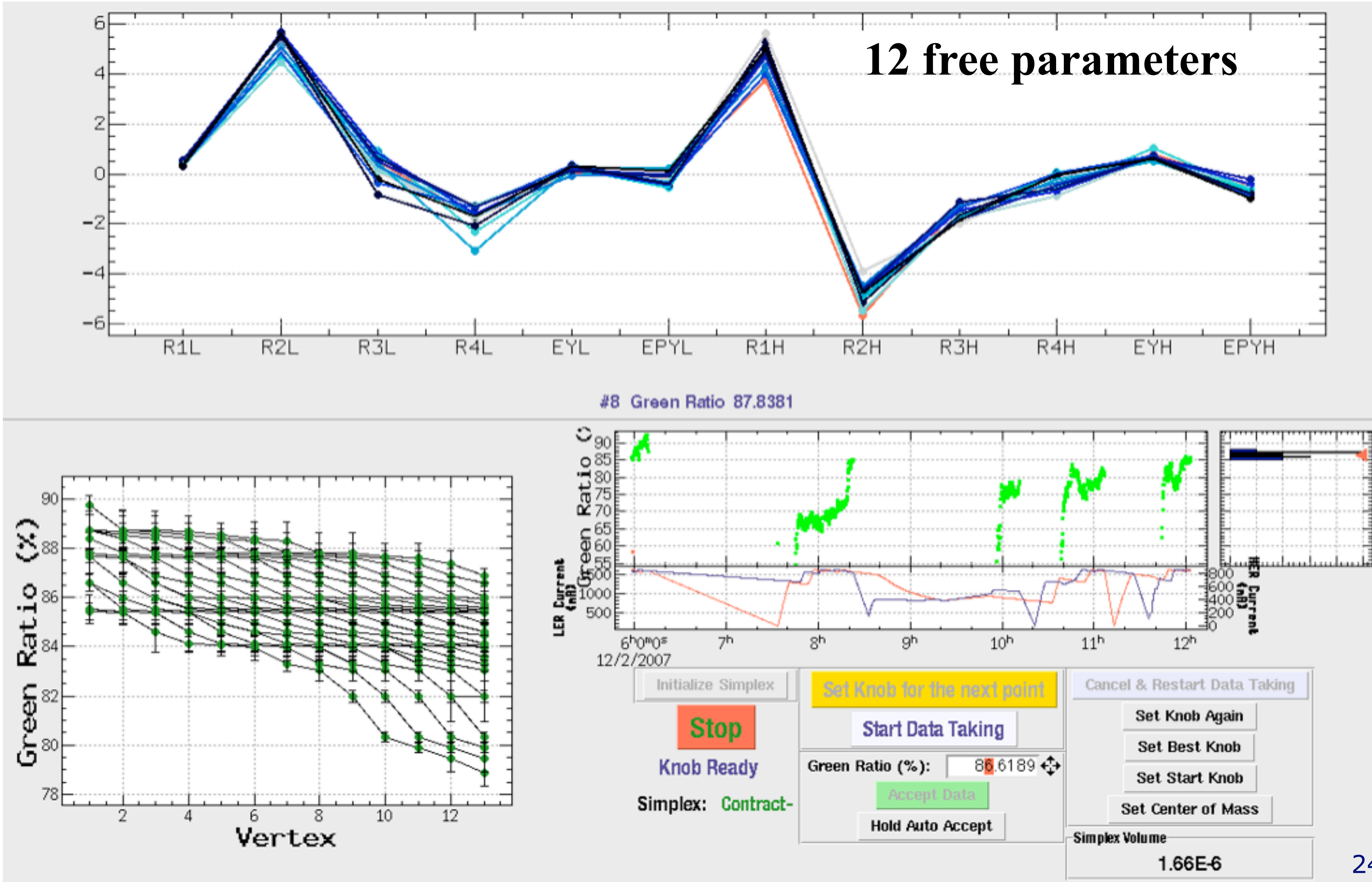
Method of Minimization

- {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

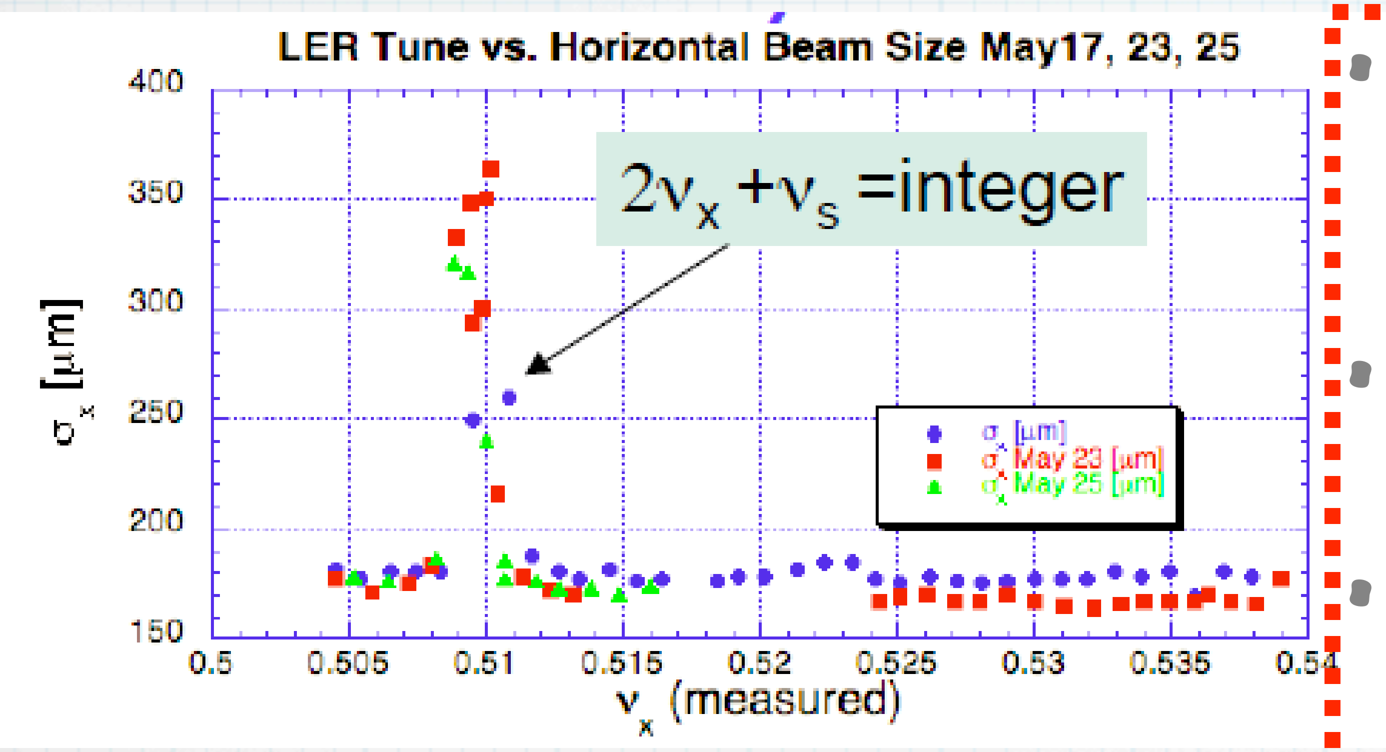


Luminosity optimization (Dec. 2)

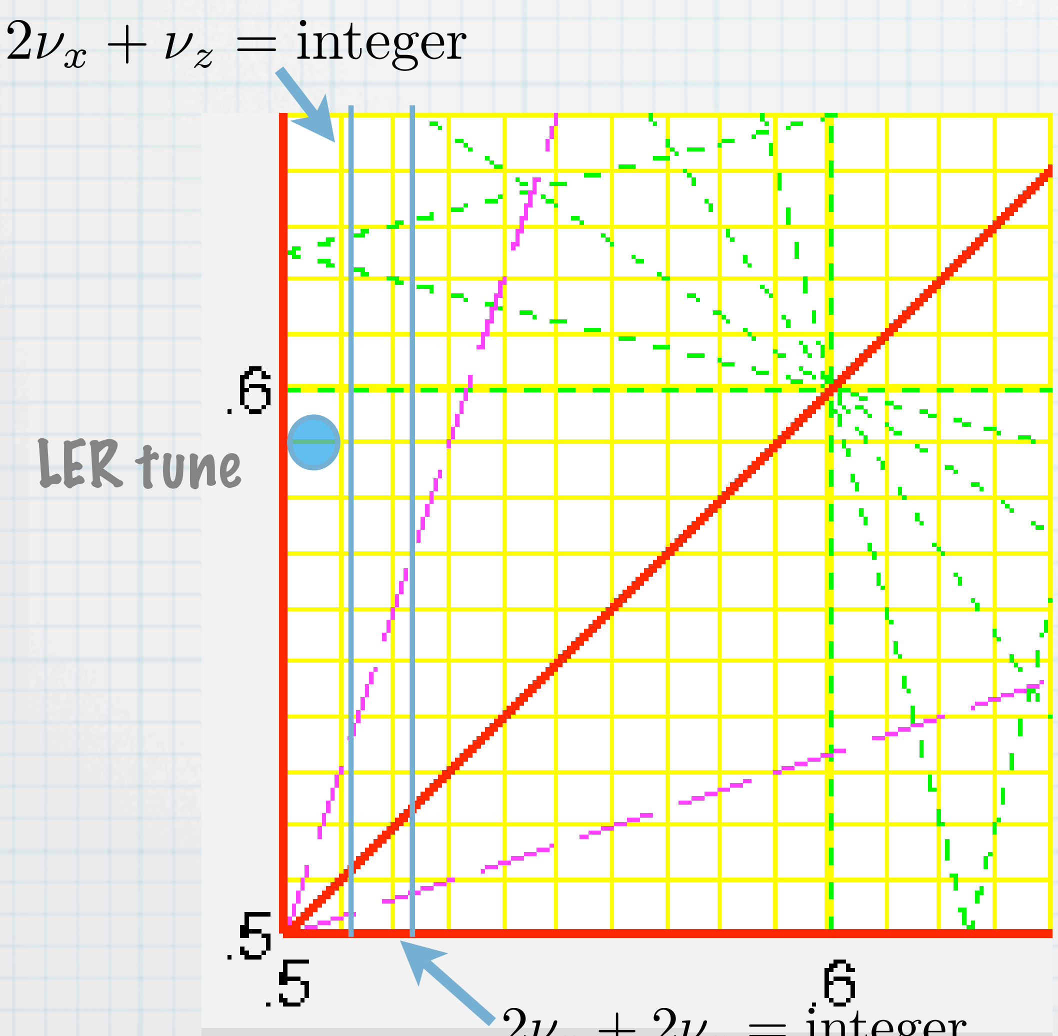
Current Simplex (Graphic View)

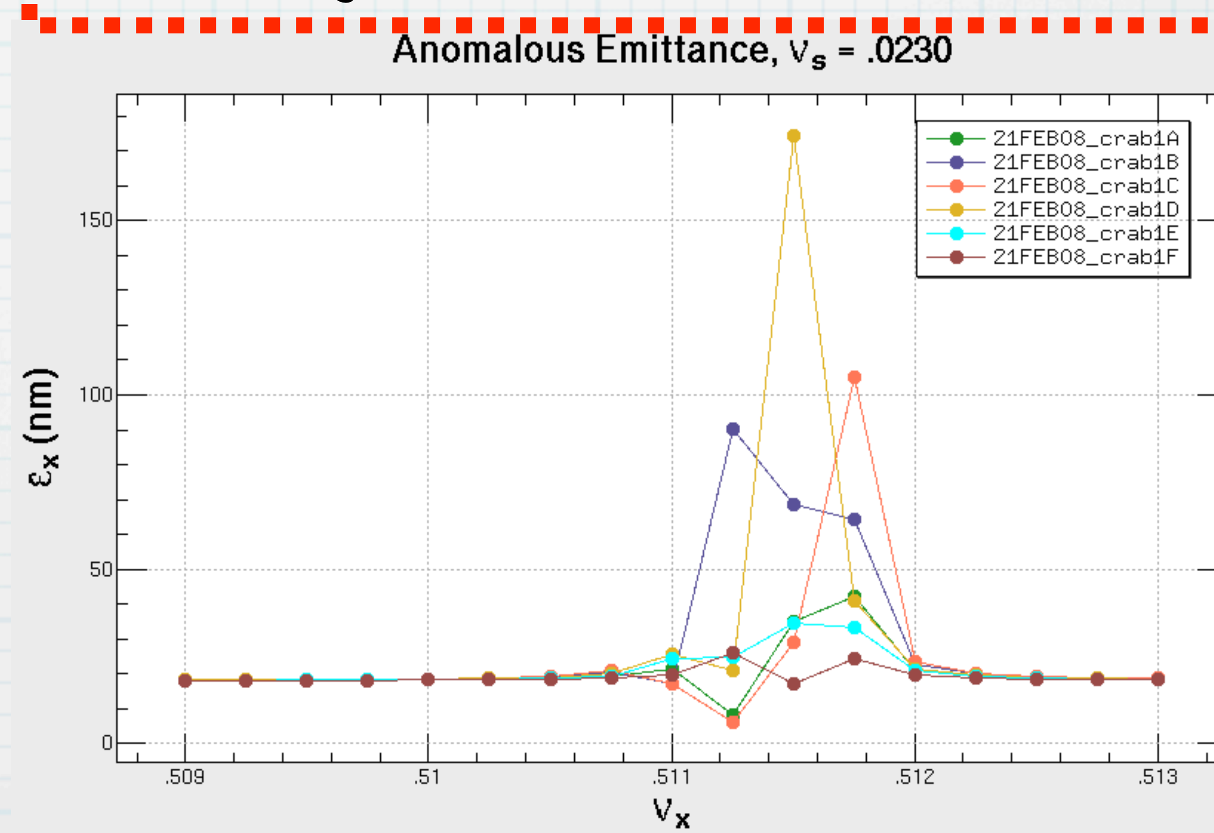


Issue 3: Synchrotron-betatron resonance

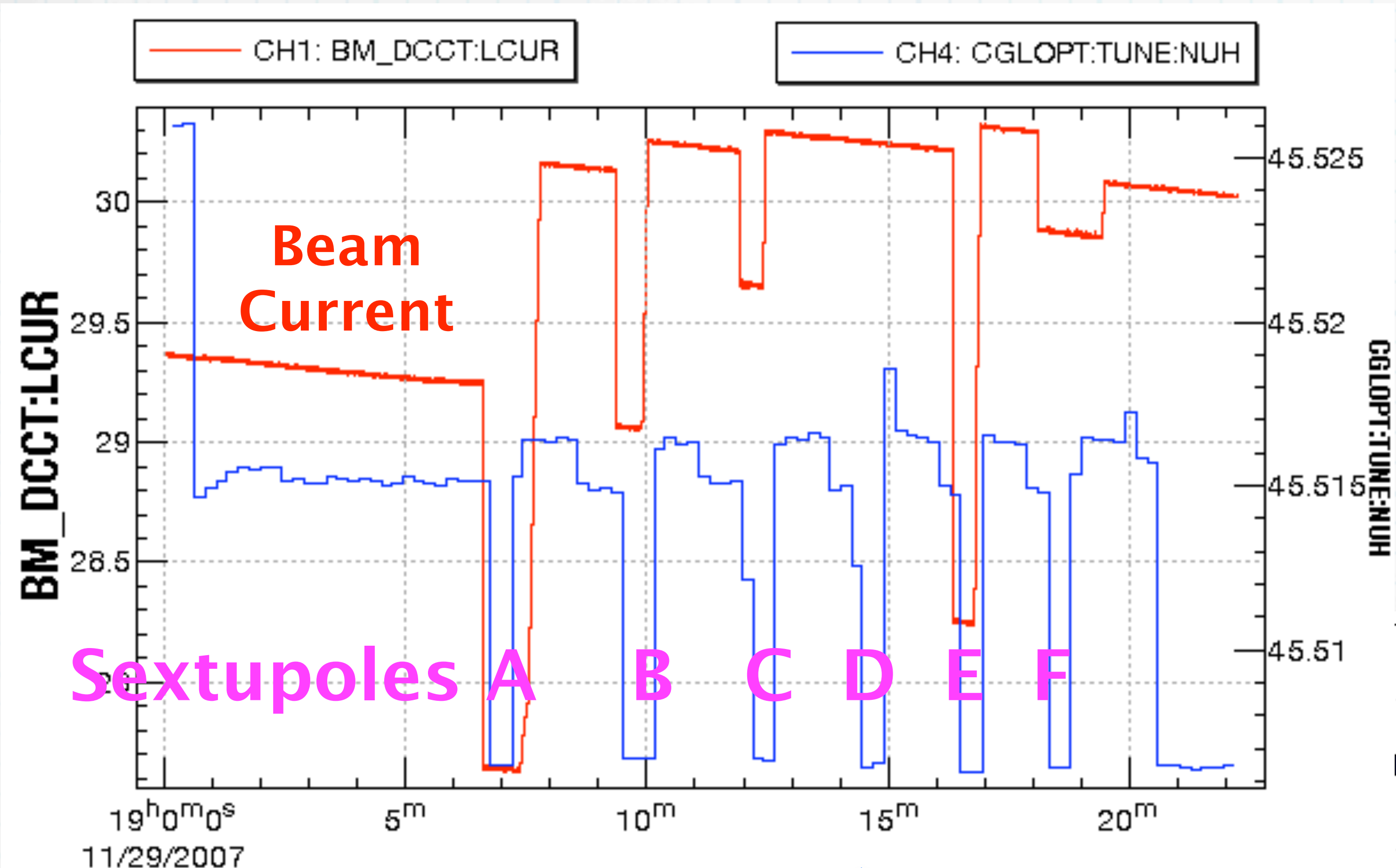


- The horizontal tune is set nearby the half integer resonace and its synchrotron sidebands.
- At the resonance, the single beam beam sizes blowup(left).
- This effect can be calculated by "anomalous emittance" effect.
- The blowup depends on the sextupole setting (below).



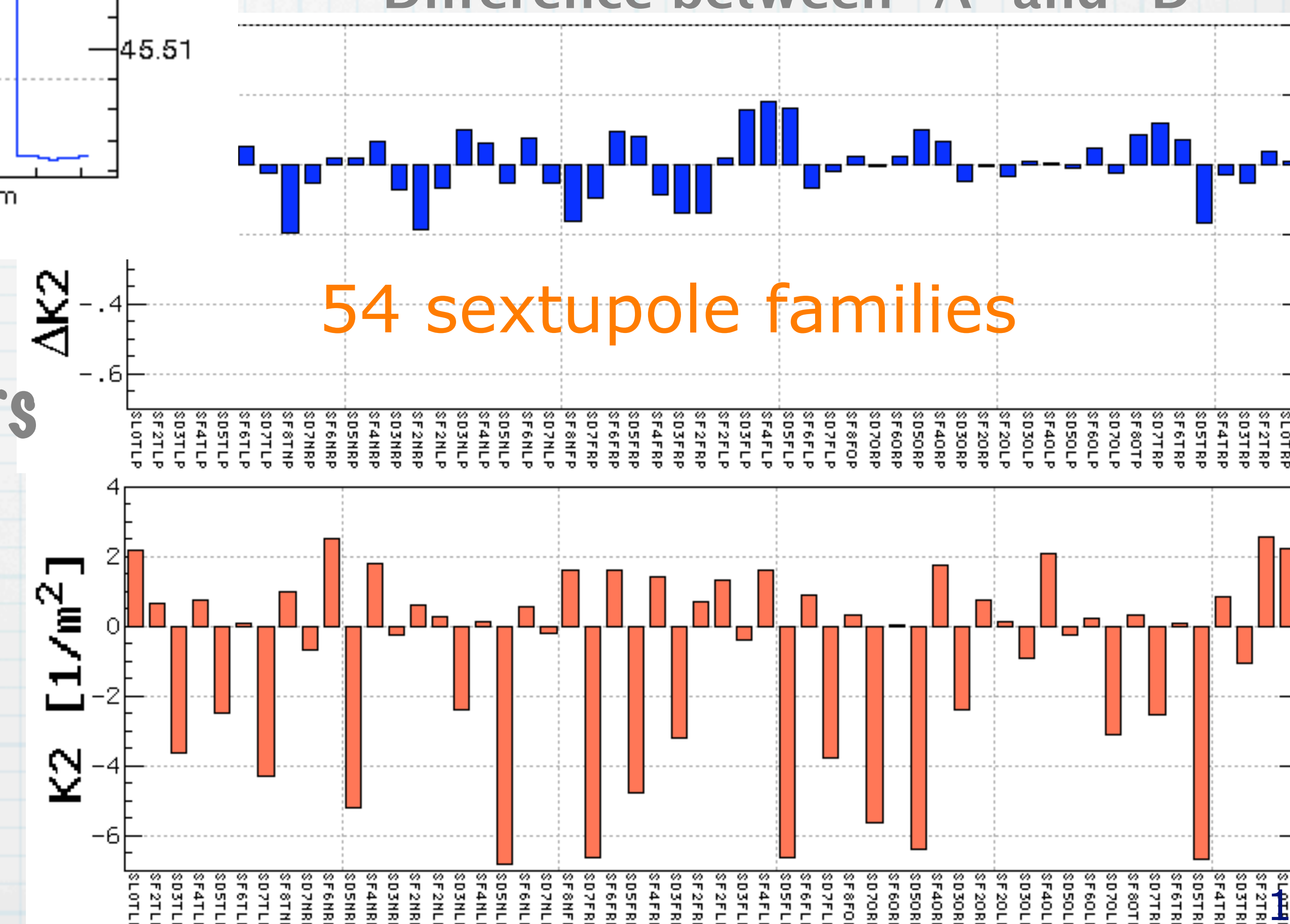


Finding better sextupole setting: "bungee jump"



- We tested 5 different sextupole configurations.
- We checked beam loss by changing tune across the resonance.

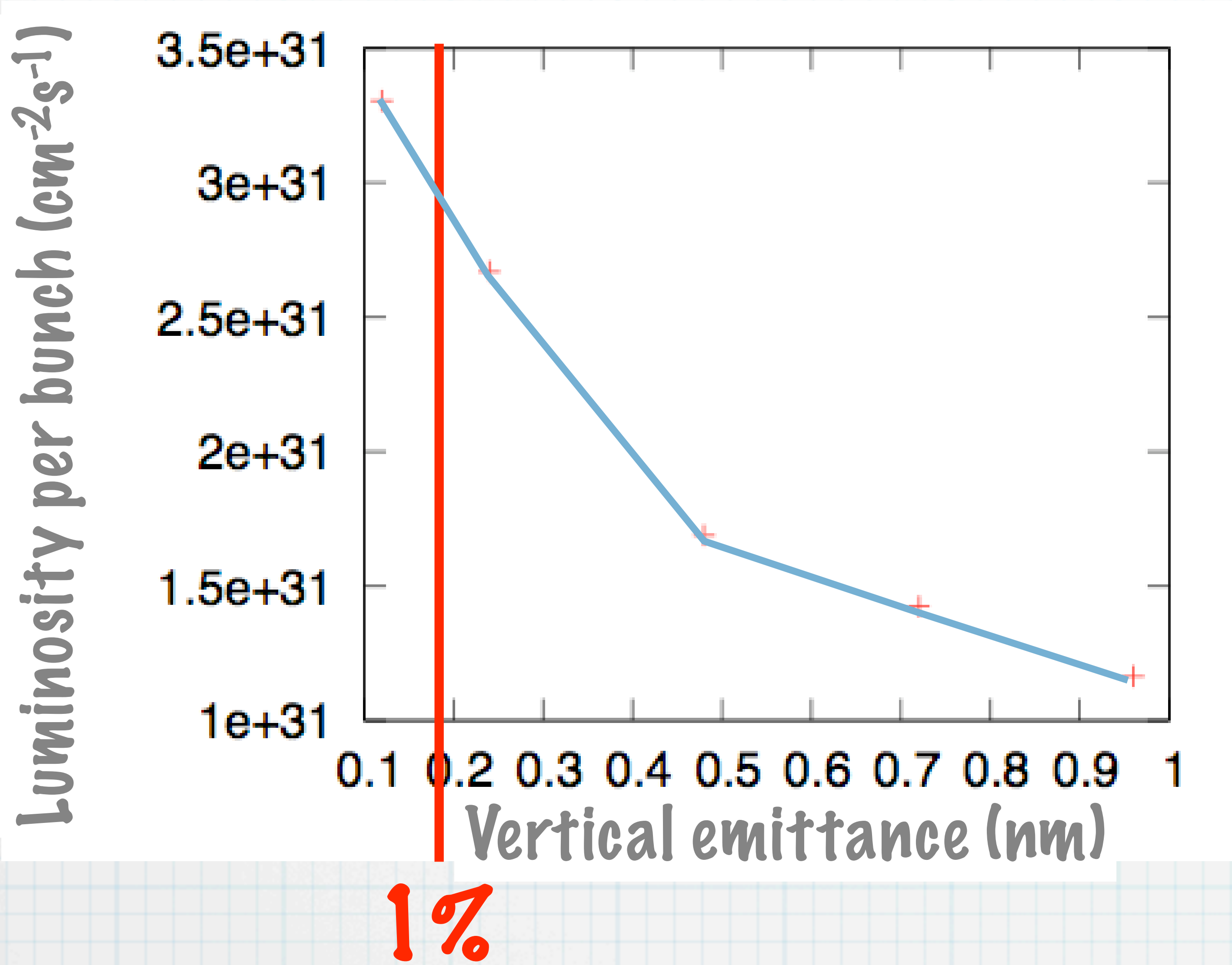
Difference between "A" and "D"



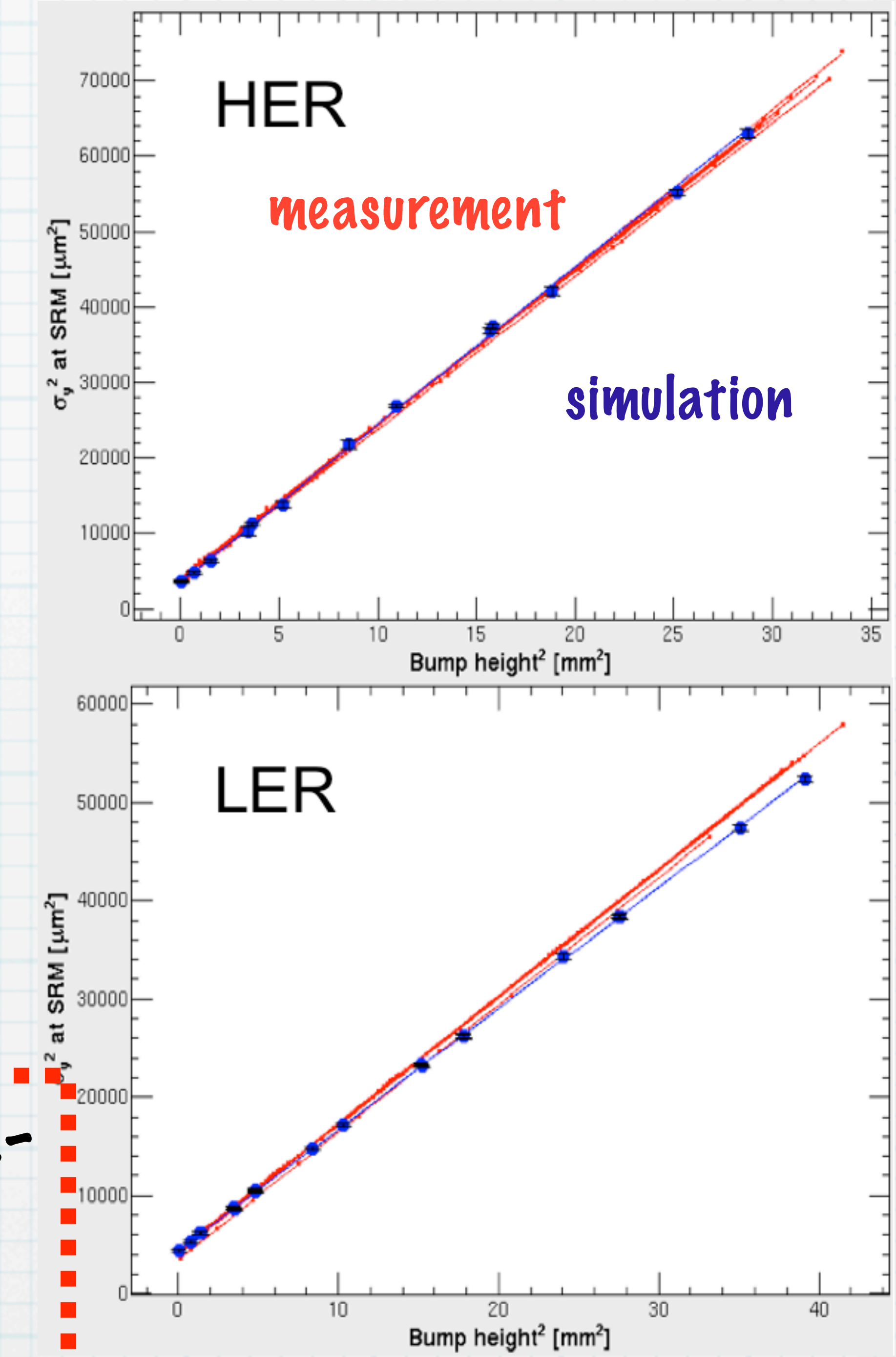
No beam loss with "D" sexts

Jumped from νx=0.516 to 0.506.
νx=.512 is the resonace
2νx+νz=integer

Vertical emittance small enough?



K. Ohmi



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- According to the simulation, the vertical single-beam emittance must be less than 1% to achieve the high luminosity(above).
- Recent calibration of the size monitor with "iSize" bump orbit shows the emittance ratio was 1.4%/1.2% for LER/HER (right).

Summary

- The crab cavities were successfully produced and installed at KEKB.
- No serious problem has been seen for the crab cavities in the beam operation since Feb. 2007.
- Single crab cavity scheme is working fine.
- Effective head-on collision was achieved.
- The crab crossing gave specific luminosity higher than the geometrical gain at least for low bunch current.
- No clear reason was confirmed why the luminosity did not reach the predicted value for higher bunch current.
- Needs more studies to reach the high luminosity predicted by simulations.