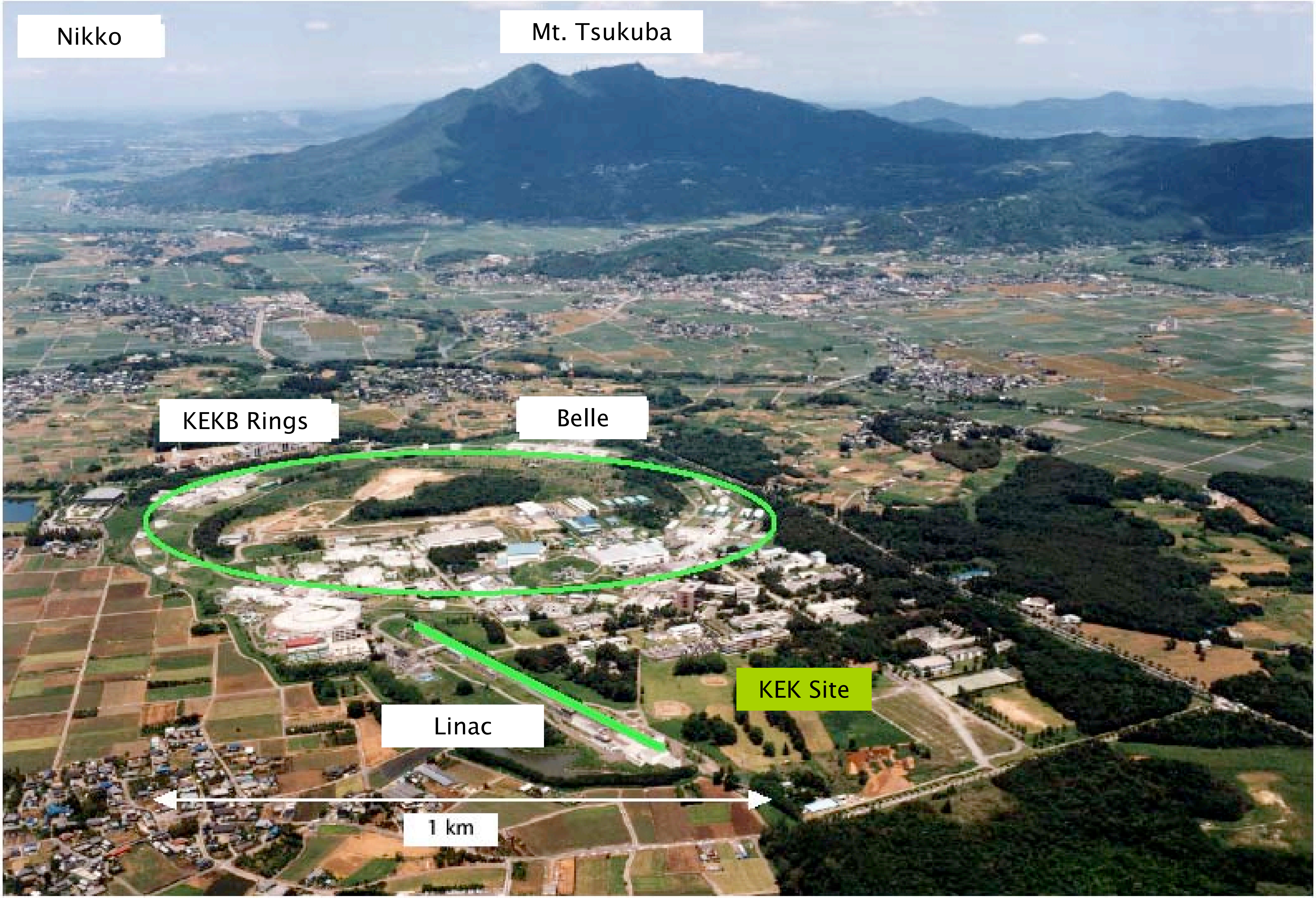
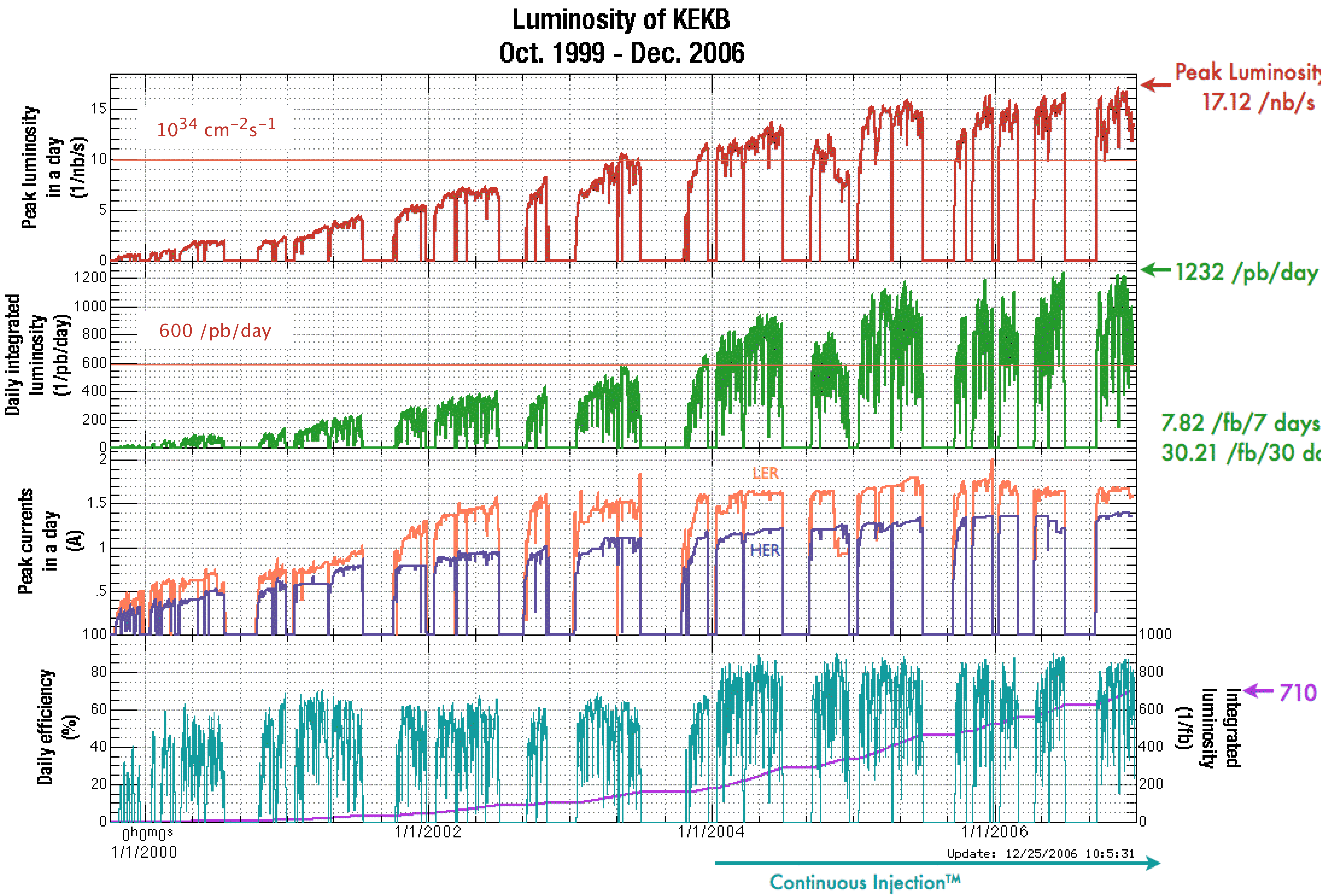
Compensation of the Crossing Angle with Crab Cavities at KEKB

First time in the world!

T. Abe, K. Akai, M. Akemoto, A. Akiyama, M. Arinaga, K. Ebihara, K. Egawa, A. Enomoto, J. Flanagan, S. Fukuda, H. Fukuma, Y. Funakoshi, K. Furukawa, T. Furuya, K. Hara, T. Higo, S. Hiramatsu, H. Hisamatsu, H. Honma, T. Honma, K. Hosoyama, T. Ieiri, N. Iida, H. Ikeda, M. Ikeda, S. Inagaki, S. Isagawa, H. Ishii, A. Kabe, E. Kadokura, T. Kageyama, K. Kakihara, E. Kako, S. Kamada, T. Kamitani, K. Kanazawa, H. Katagiri, S. Kato, T. Kawamoto, S. Kazakov, M. Kikuchi, E. Kikutani, K. Kitagawa, H. Koiso, Y. Kojima, I. Komada, T. Kubo, K. Kudo, N. Kudo, K. Marutsuka, M. Masuzawa, S. Matsumoto, T. Matsumoto, S. Michizono, K. Mikawa, T. Mimashi, S. Mitsunobu, K. Mori, A. Morita, Y. Morita, H. Nakai, H. Nakajima, T. T. Nakamura, H. Nakanishi, K. Nakanishi, K. Nakao, S. Ninomiya, Y. Ogawa, K. Ohmi, S. Ohsawa, Y. Ohsawa, Y. Ohnishi, N. Ohuchi, K. Oide, M. Ono, T. Ozaki, K. Saito, H. Sakai, Y. Sakamoto, M. Sato, M. Satoh, K. Shibata, T. Shidara, M. Shirai, A. Shirakawa, T. Sueno, M. Suetake, Y. Suetsugu, R. Sugahara, T. Sugimura, T. Suwada, O. Tajima, S. Takano, S. Takasaki, T. Takenaka, Y. Takeuchi, M. Tawada, M. Tejima, M. Tobiyama, N. Tokuda, S. Uehara, S. Uno, Y. Yamamoto, Y. Yano, K. Yokoyama, Ma. Yoshida, Mi. Yoshida, S. Yoshimoto, K. Yoshino,
KEK, Oho, Tsukuba, Ibaraki 305-0801, Japan
E. Perevedentsev, D. N. Shatilov, BINP, Novosibirsk, Russia

PAC07, 25 June 2007, MOZAKI01
Speaker: K. Oide


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



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

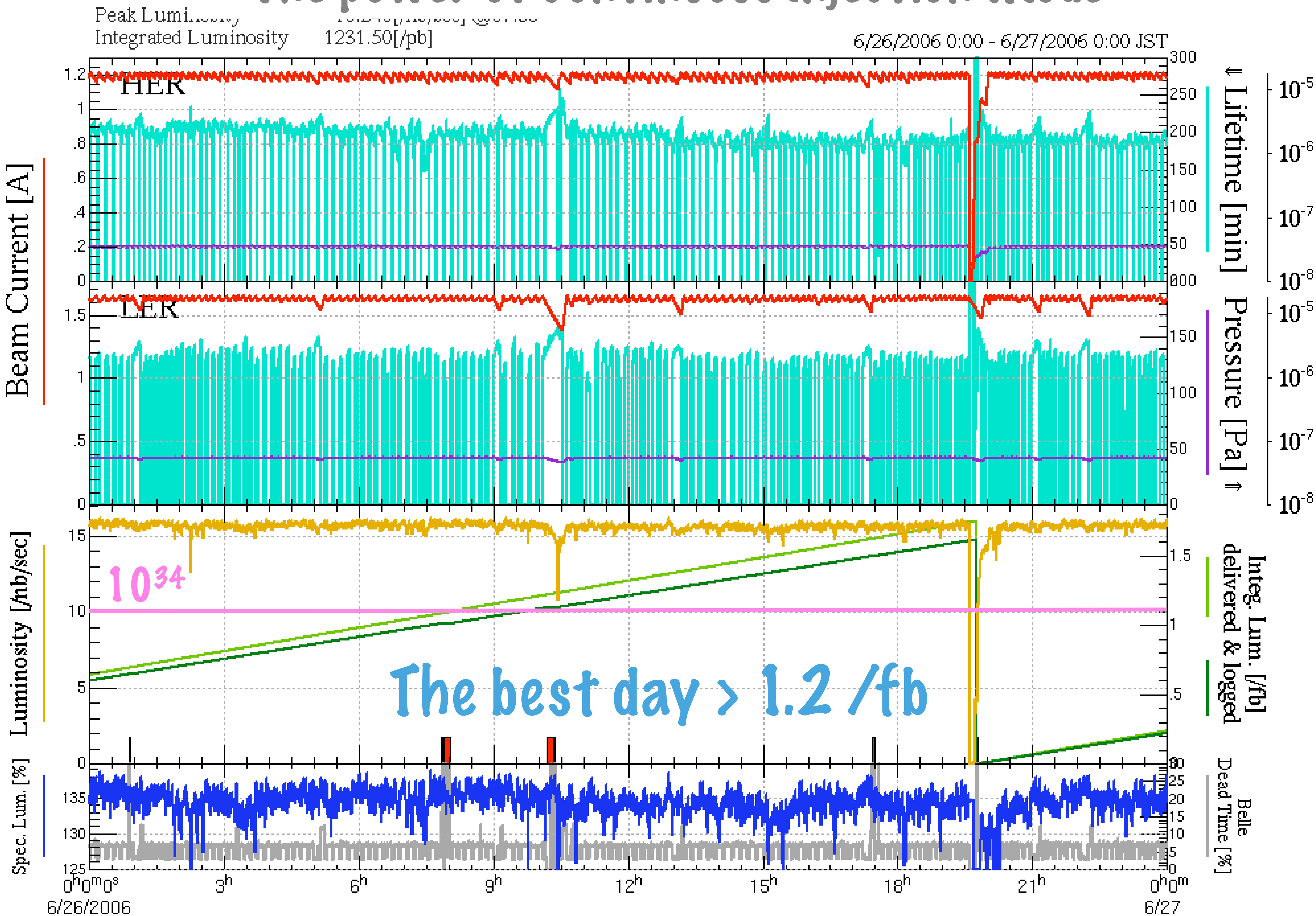
Table 1: Machine parameters of KEKB

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

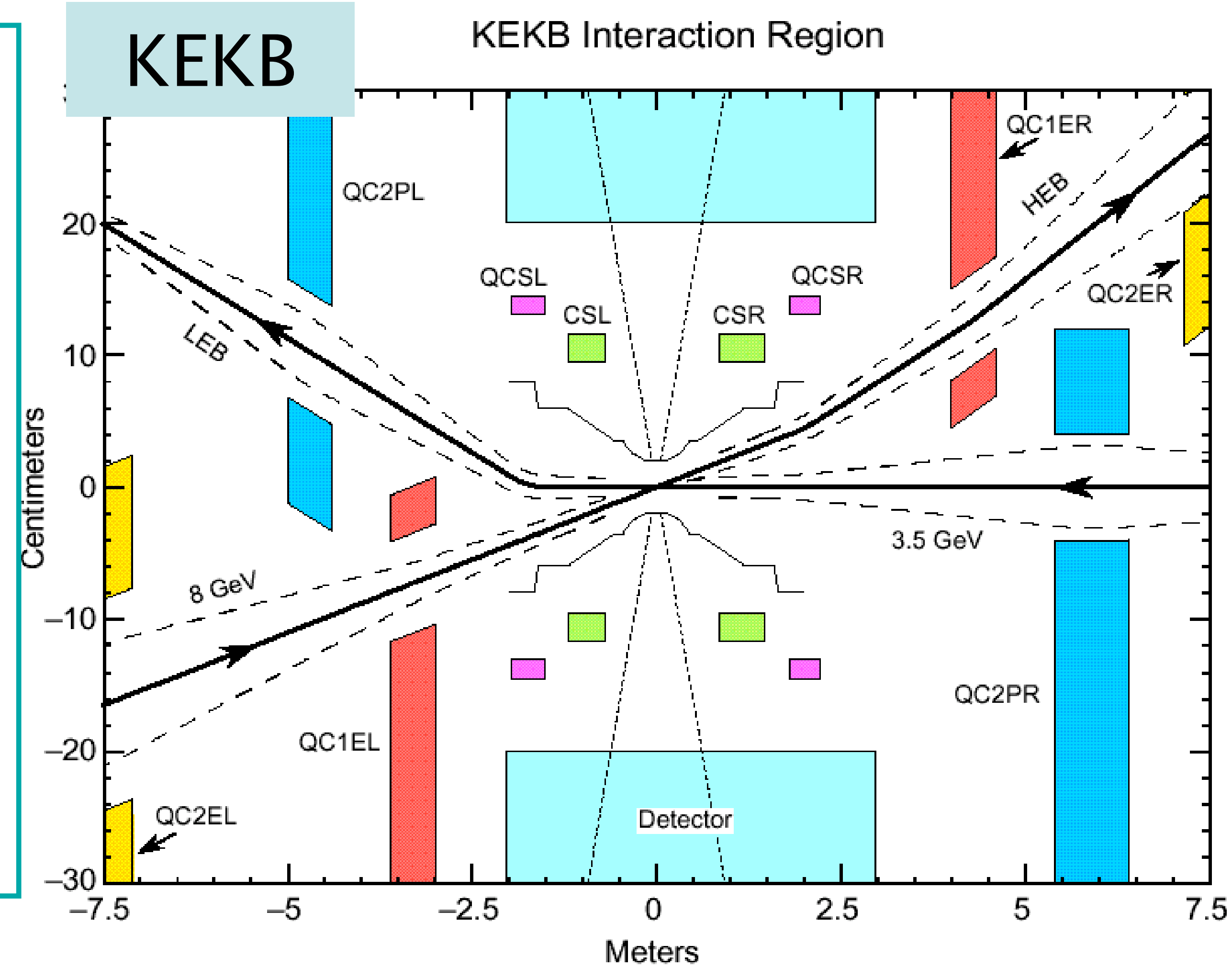
doubled the design

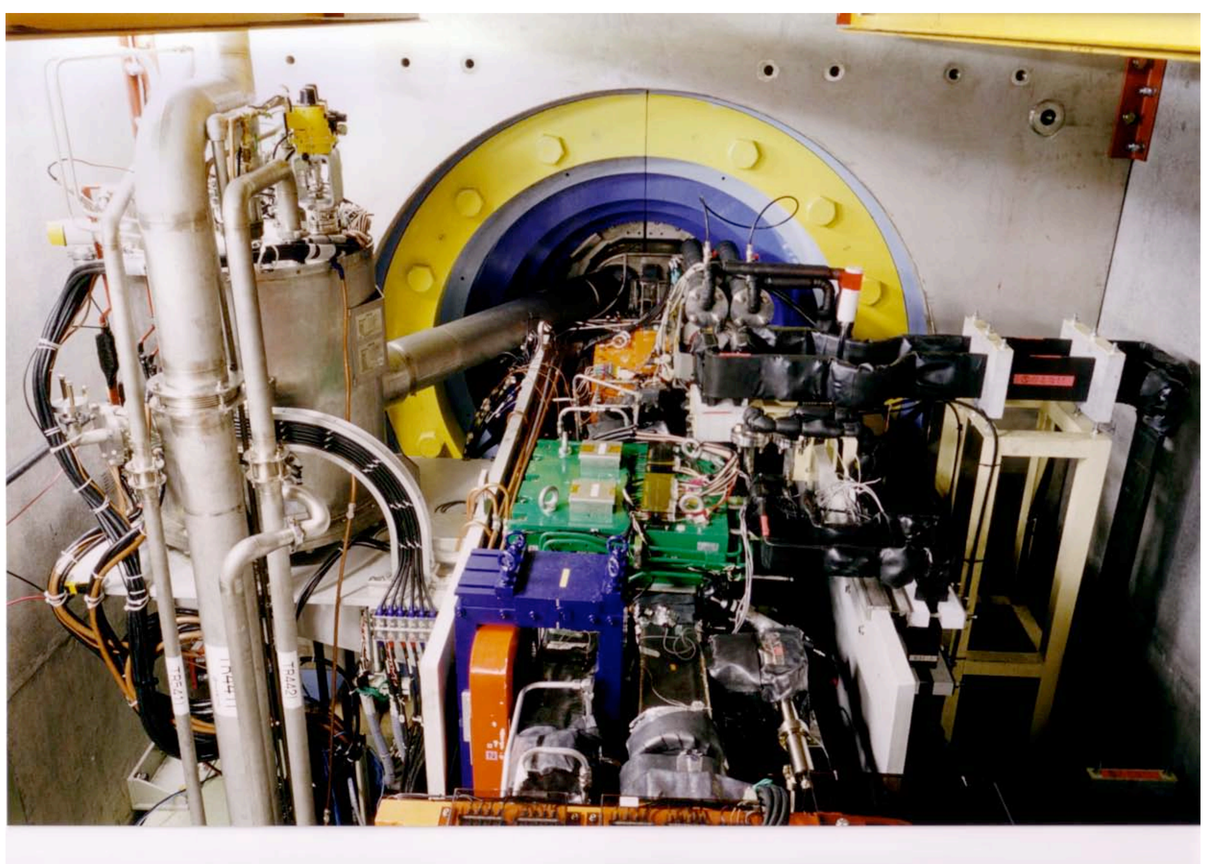
The power of Continuous Injection Mode

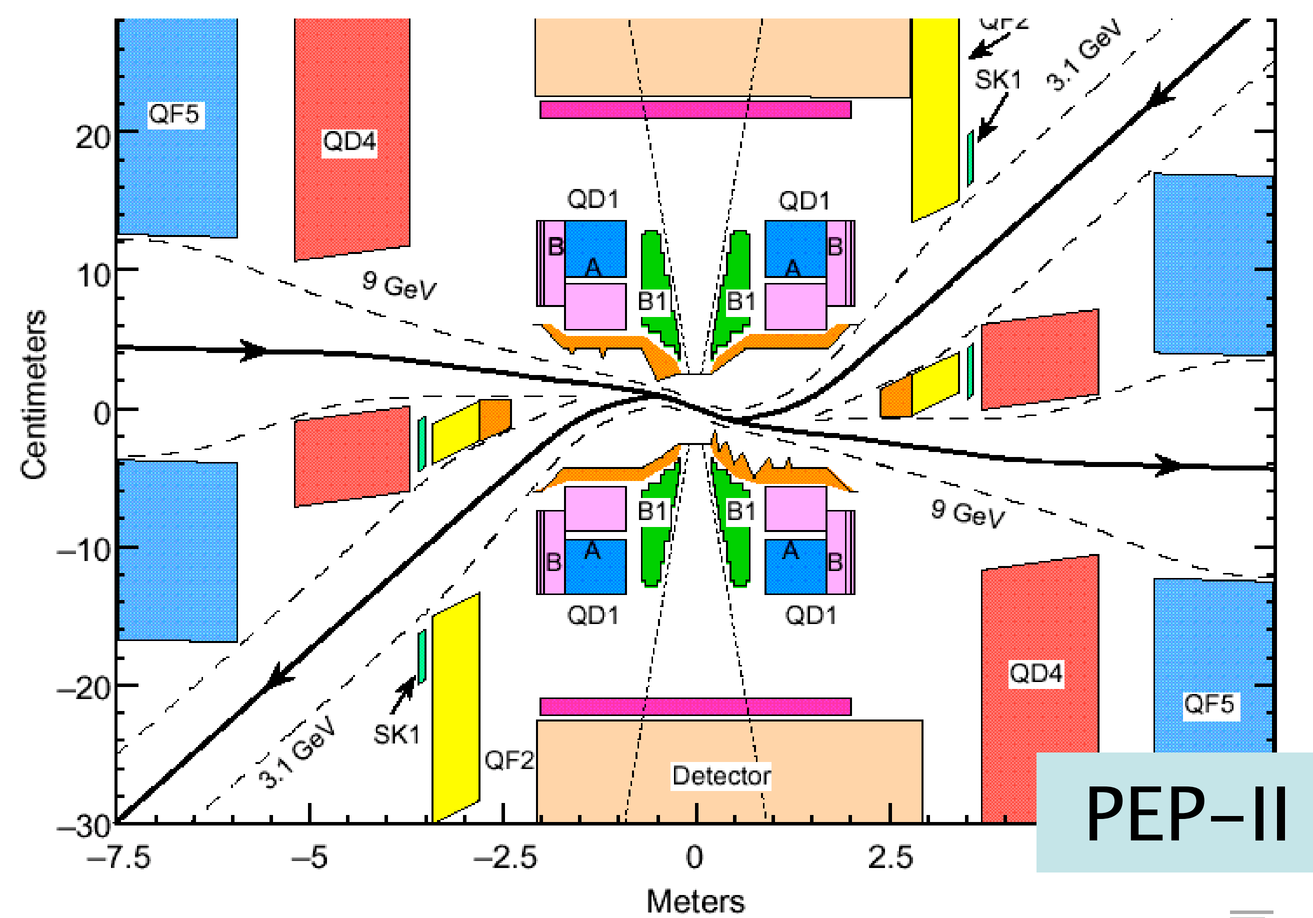


KEKB has 22 mrad horizontal crossing angle at the IP:

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



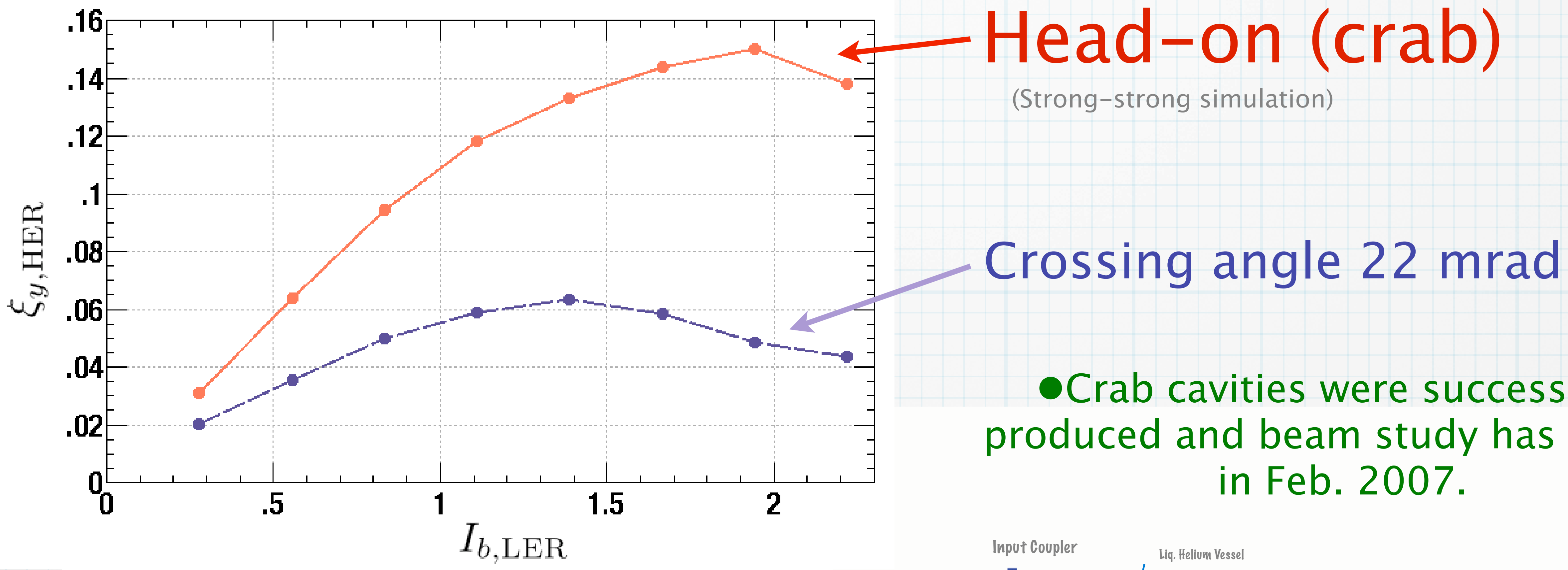




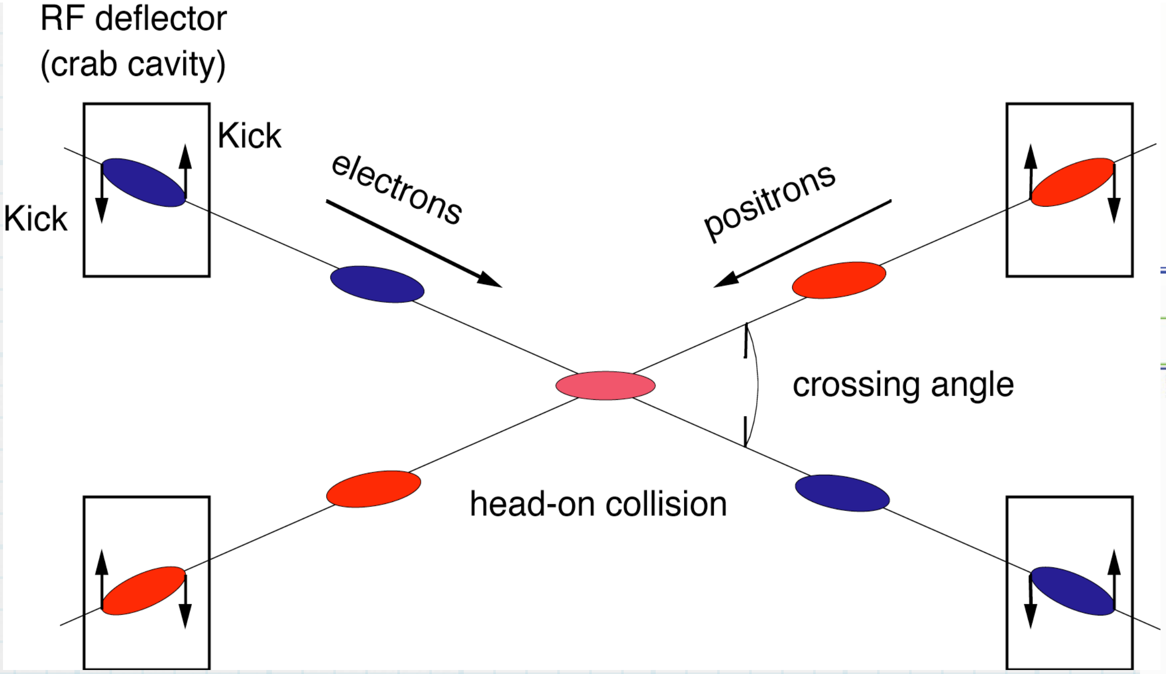
Crab Crossing @ KEKB

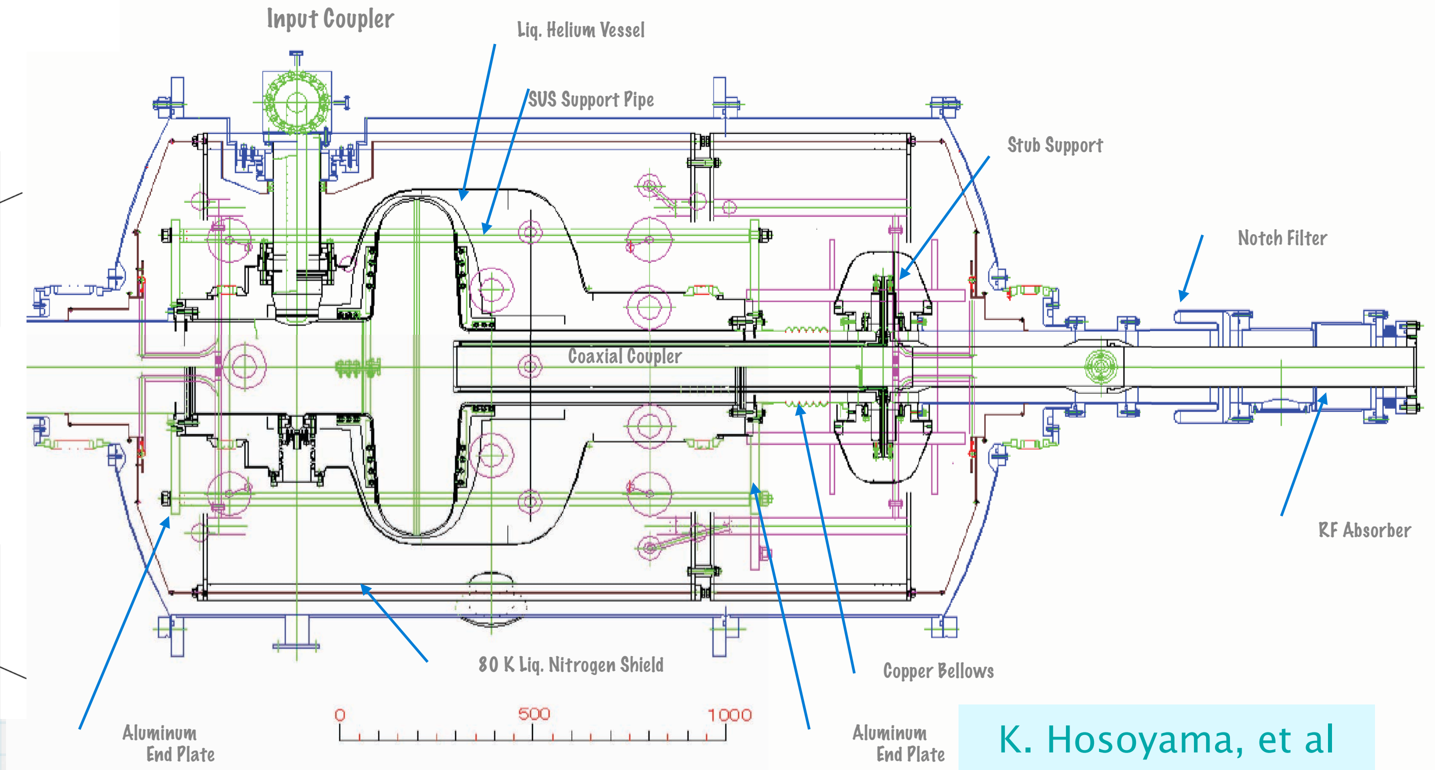
- Crab Crossing can boot the beam-beam parameter higher than 0.15 !

K. Ohmi



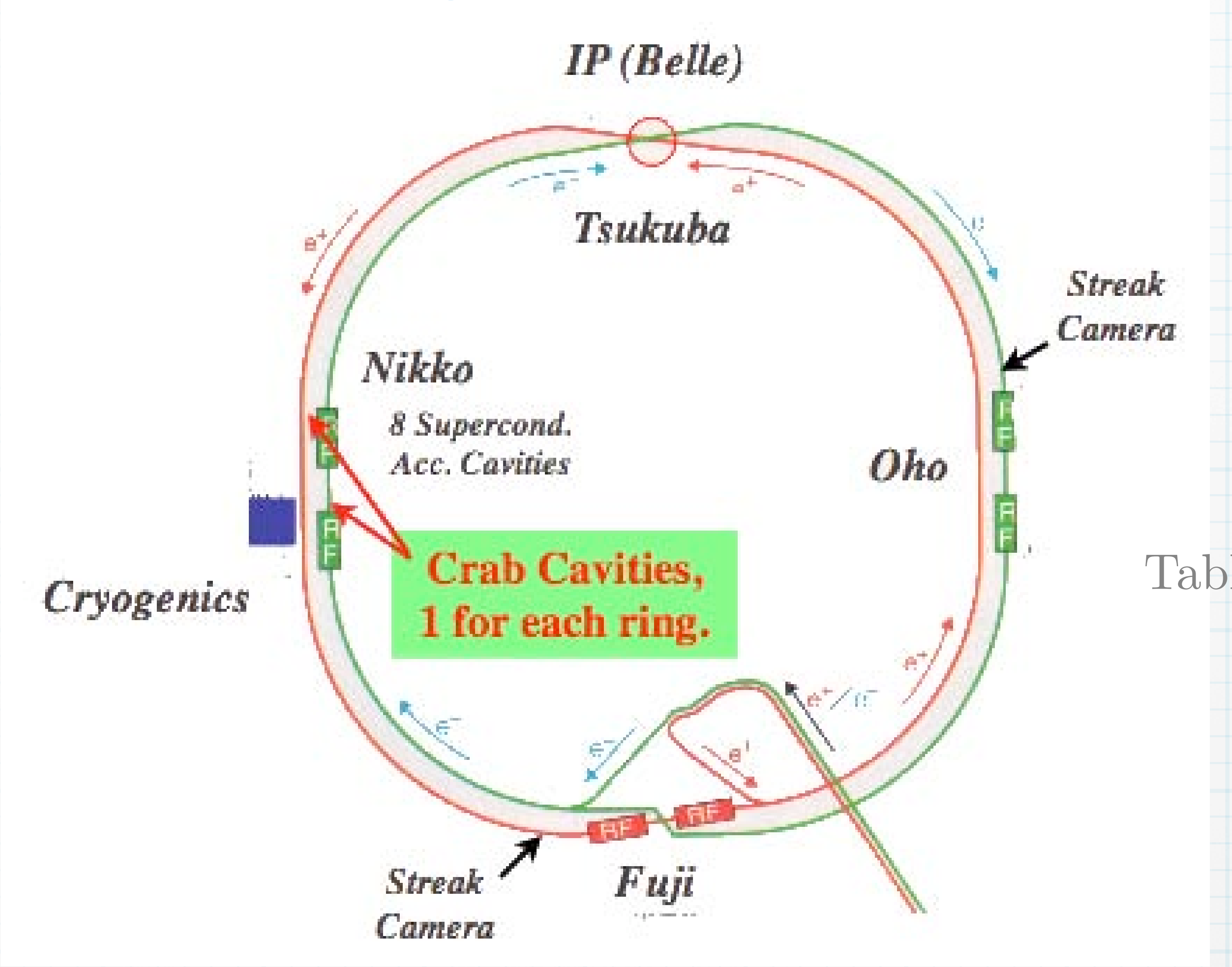
- Crab cavities were successfully produced and beam study has started in Feb. 2007.





K. Hosoyama, et al

Single Crab Cavity Scheme



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

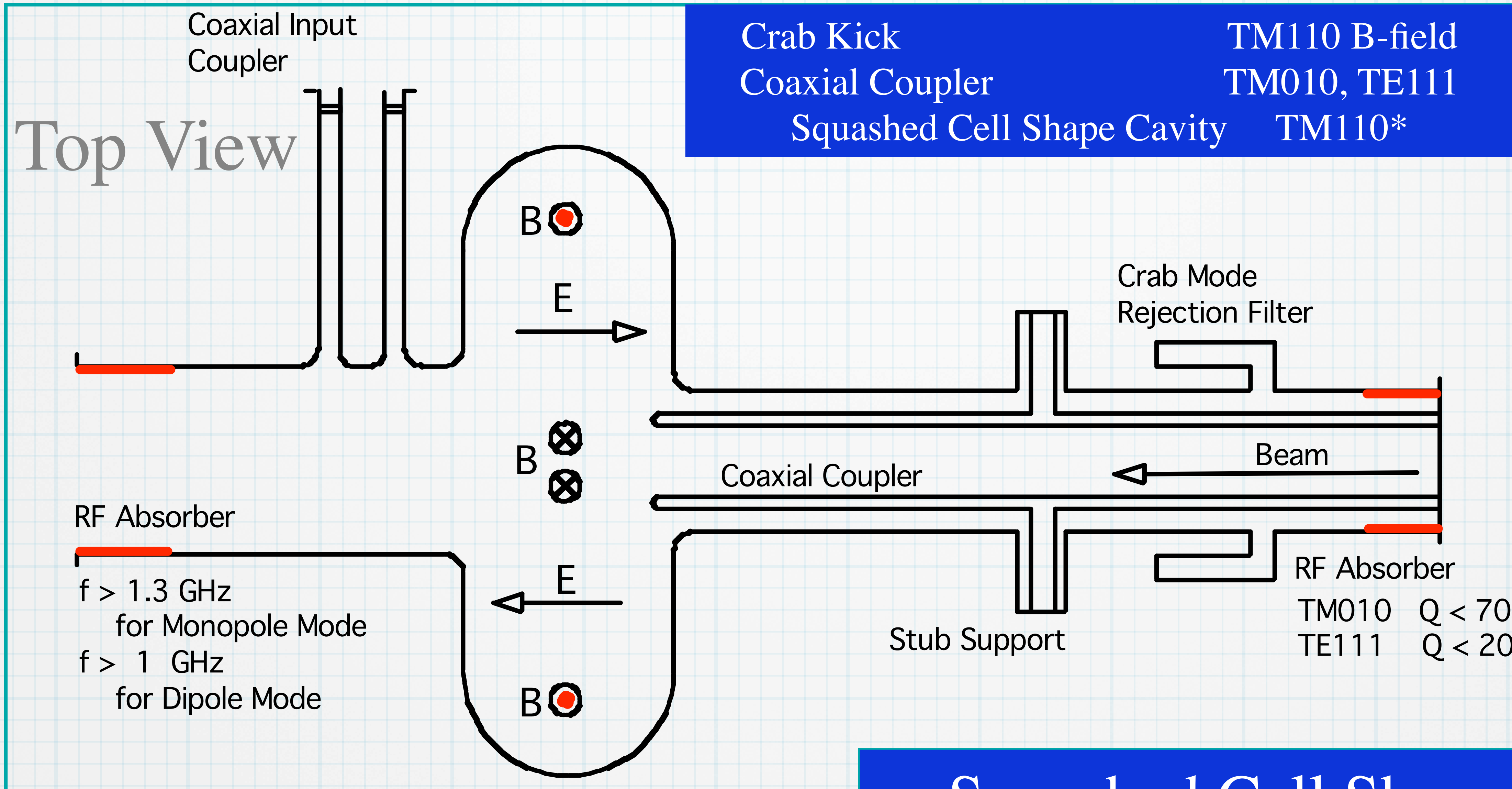
$$\frac{\theta_x}{2} = \frac{\sqrt{\beta_x^C \beta_x^*}\cos(\psi_x^C - \mu_x/2)}{2\sin(\mu_x/2)} \frac{V_C \omega_{\rm rf}}{Ec}$$

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

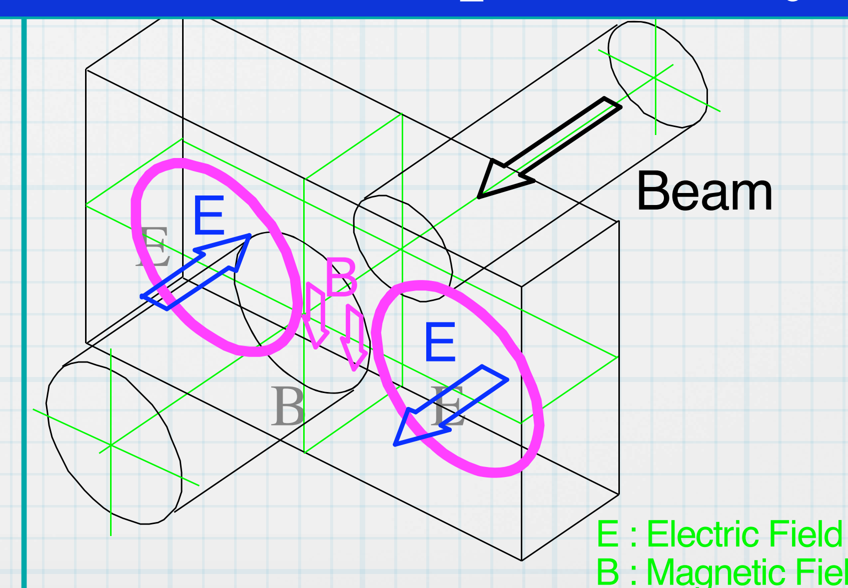
* 1 crab cavity per ring.
* saves the cost of the cavity and cryogenics.
* avoids synchrotron radiation hitting the cavity.

Concept of the KEKB Crab Cavity



Crab Kick	TM110 B-field
Coaxial Coupler	TM010, TE111
Squashed Cell Shape Cavity	TM110*

Squashed Cell Shape Cavity

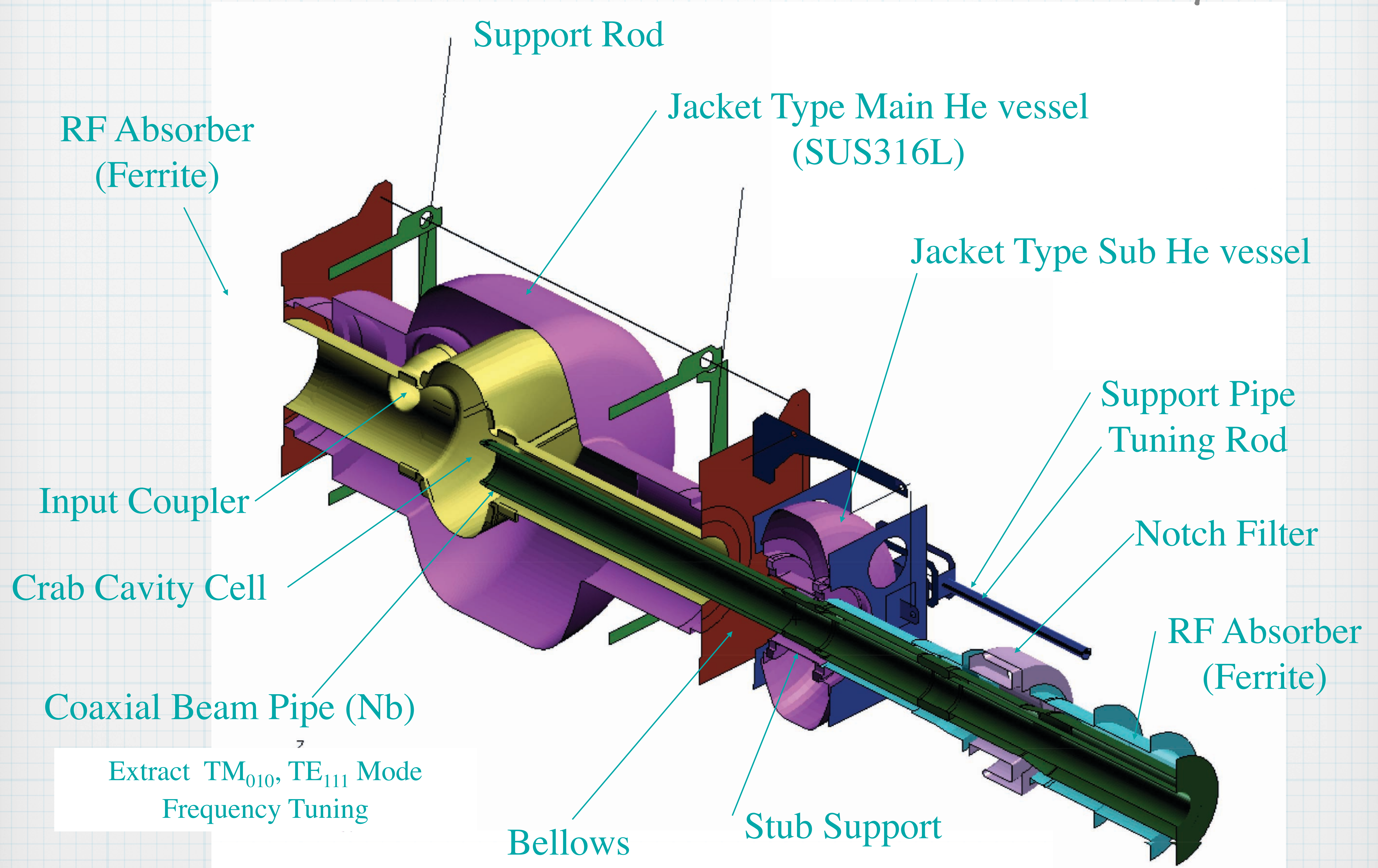


The squashed cell shape cavity scheme was studied extensively by K. Akai at Cornell in 1991 and 1992 for CESR-B under KEK-Cornell collaboration.

We adopted this design as “base design”!

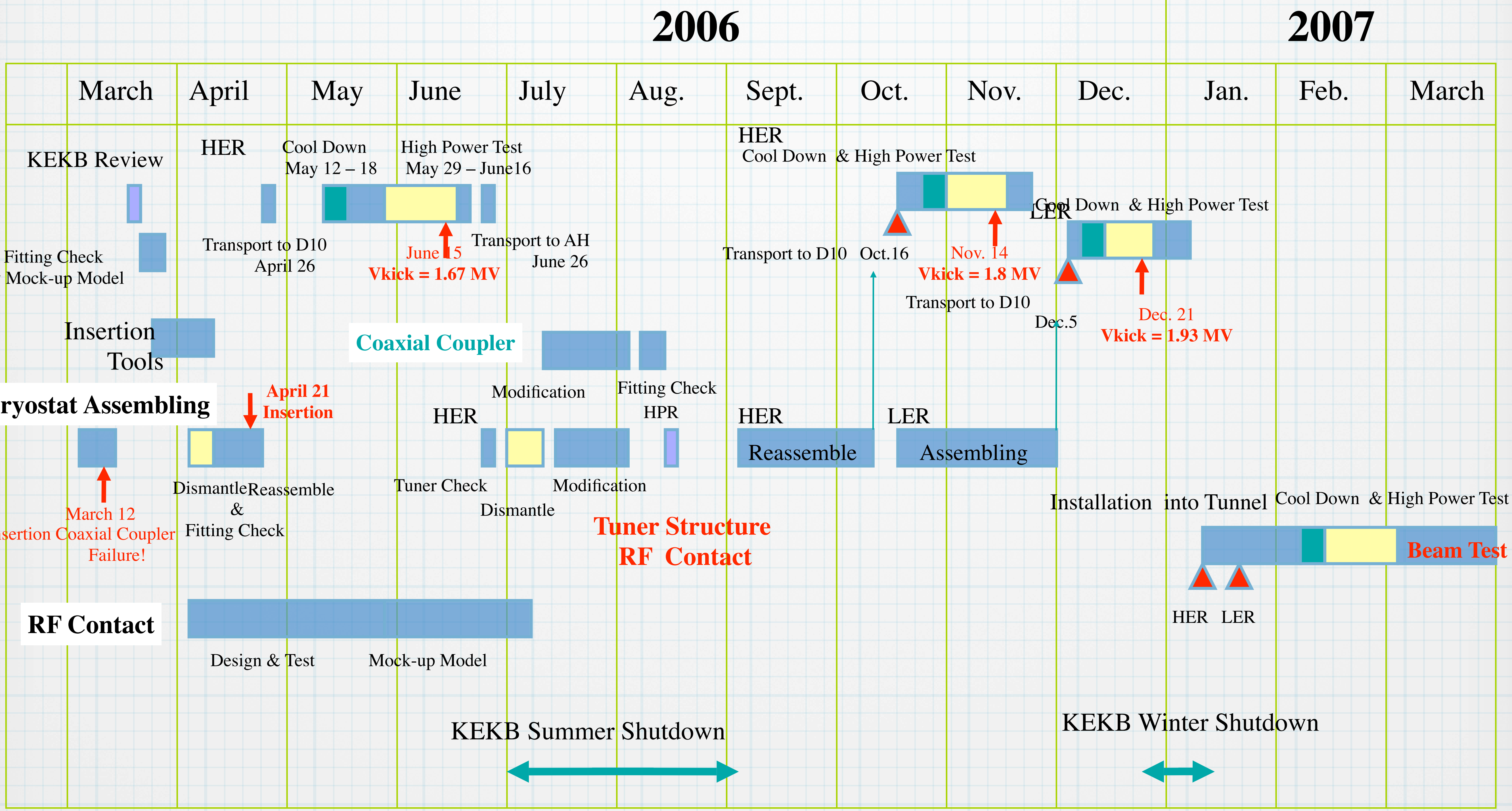
Crab Cavity & Coaxial Coupler in Cryomodule

K. Hosoyama et al



Construction & High Power Test of Crab Cavities

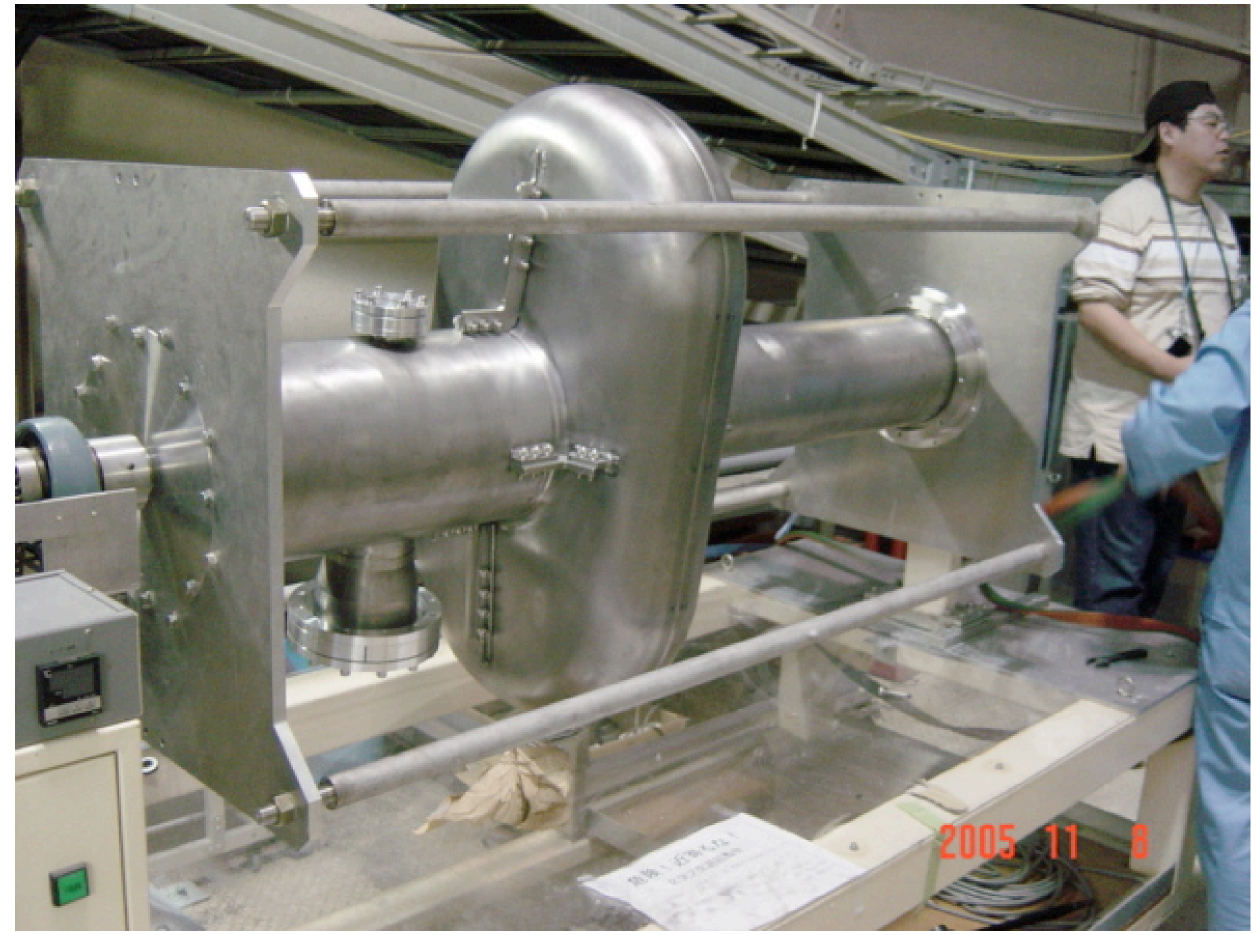
Jan. 20, 2007
K. Hosoyama



Forming and Barrel Polishing

Forming of 4 Half-Cells for Crab Cavity for LER and HER

Feb. 14, 2005 at Mitsubishi Heavy Industries, LTD. Kobe

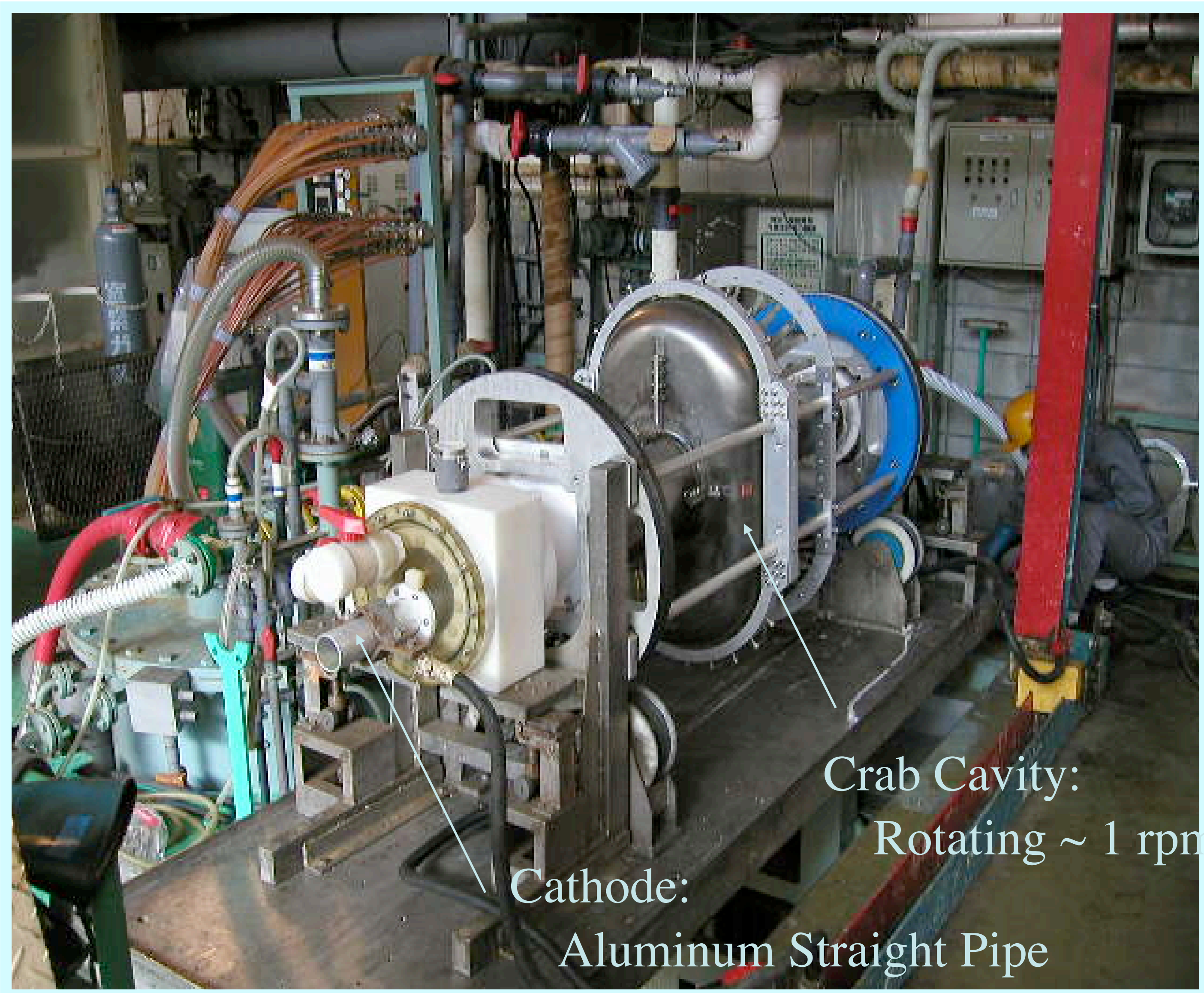


Barrel Polishing

Polishing Time 312 Hr

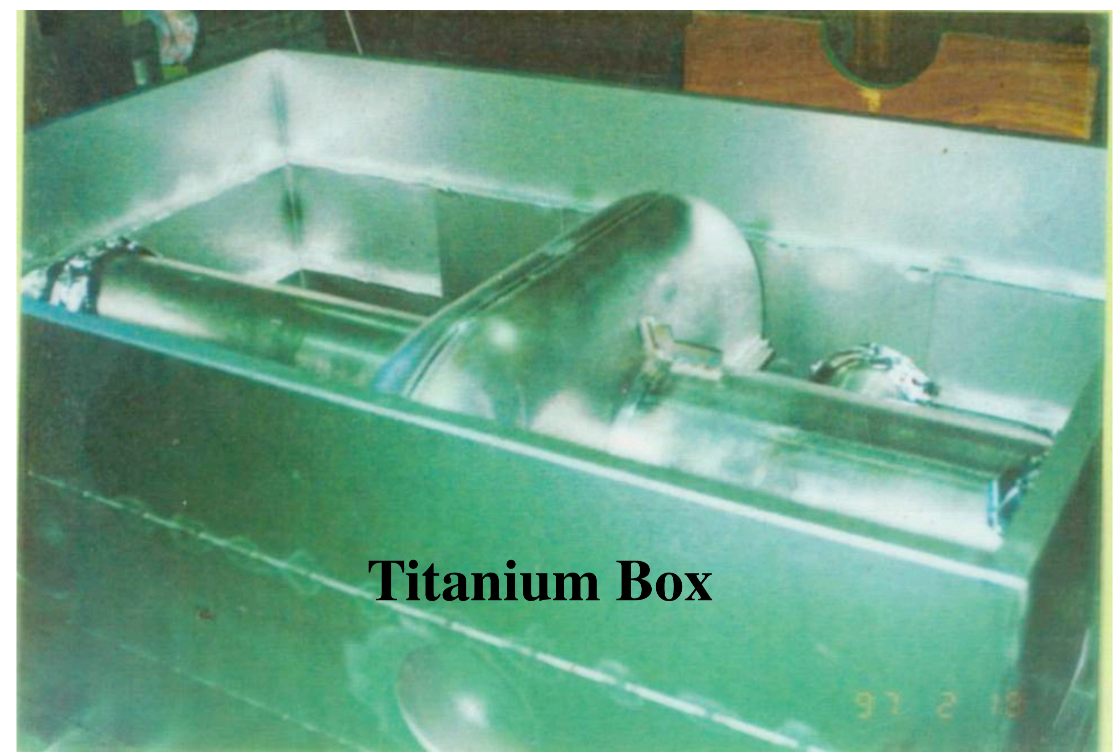
Nov. 11, 2005 at KEK

Electro Polishing & Annealing



Electro Polishing at Nomura Plating Ltd.

EP 1 ~ 100 μm
EP 2 ~ 5 μm



Annealing at 700°C for 3 hours at Kinzoku Giken Ltd.

High Pressure Rinsing and Assembling for RF Cold Test

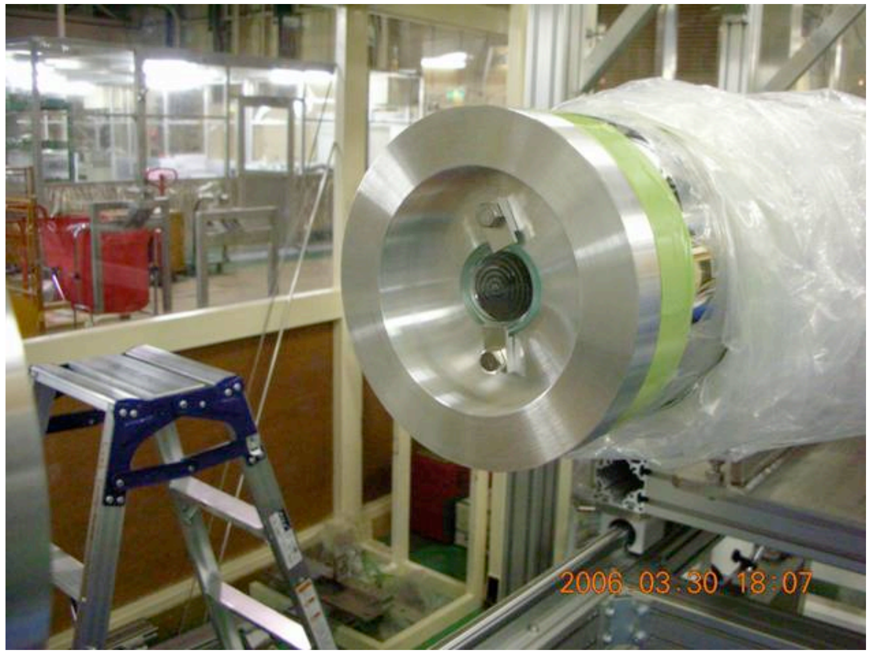
Set Flanges of Beam Pipes and Ports
in Class 100 Clean Room

High Pressure Water Rinsing
by 80 bar Ultra-Pure water

Rotation & Up-Down Motion

Alignment of Coaxial Coupler

Decide the axis of the coaxial coupler
set in the cryostat by using transit.



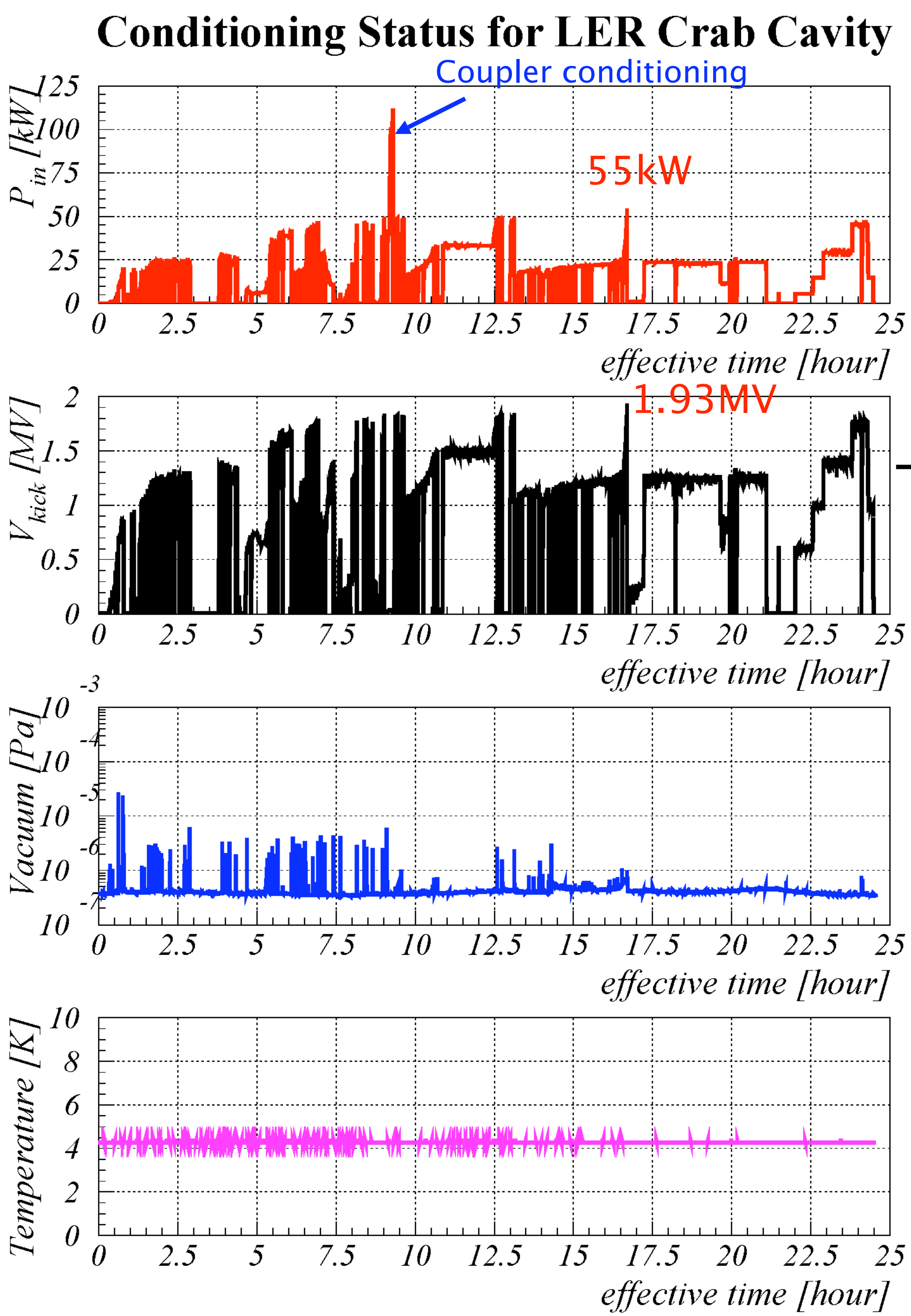
Align the axis of the coaxial coupler
which will be connected to the coaxial
coupler of cryostat side.

Move to Test Stand for Cool-down & High Power Test

RF Conditioning in Horizontal Tests

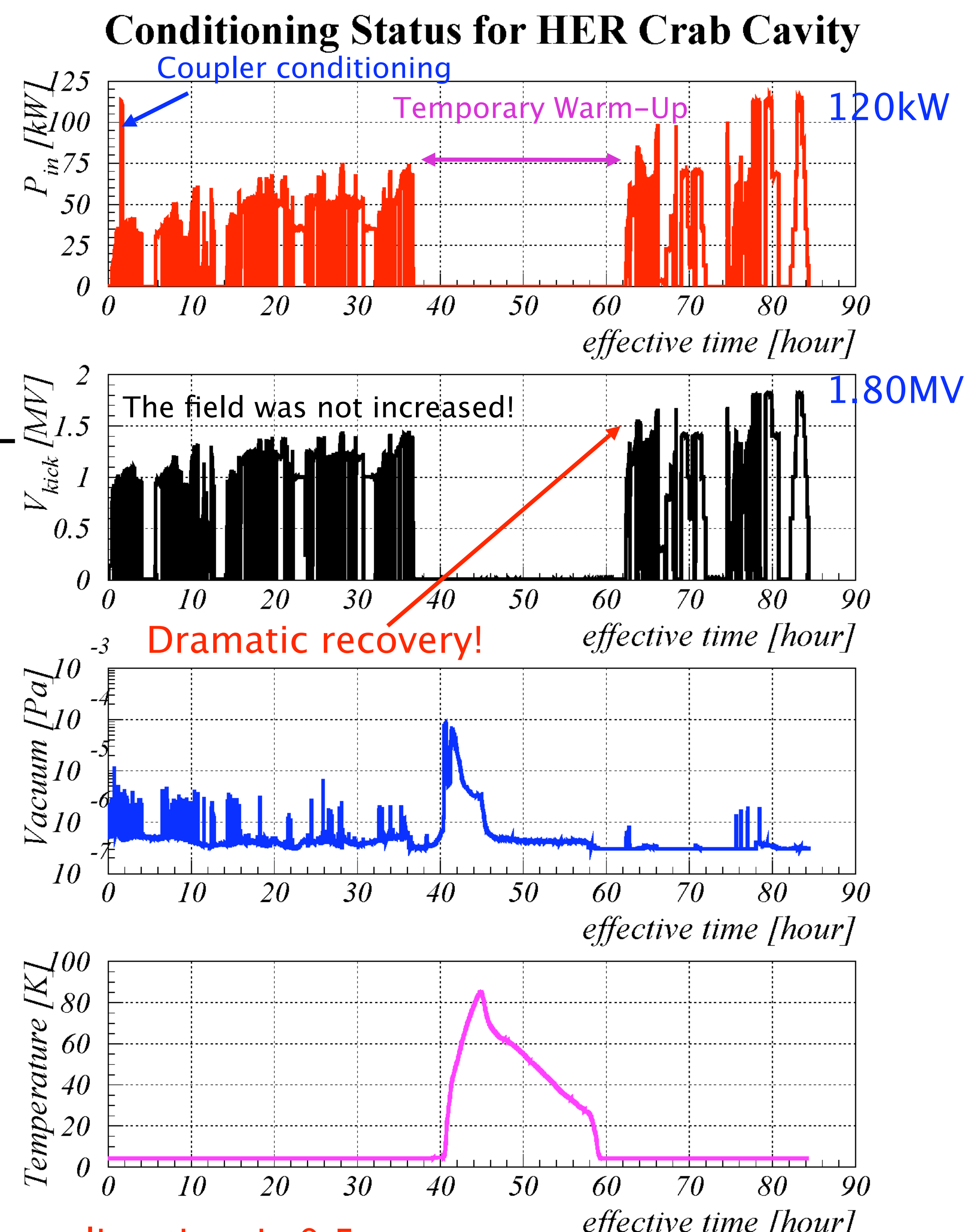
LER

HER



Goal

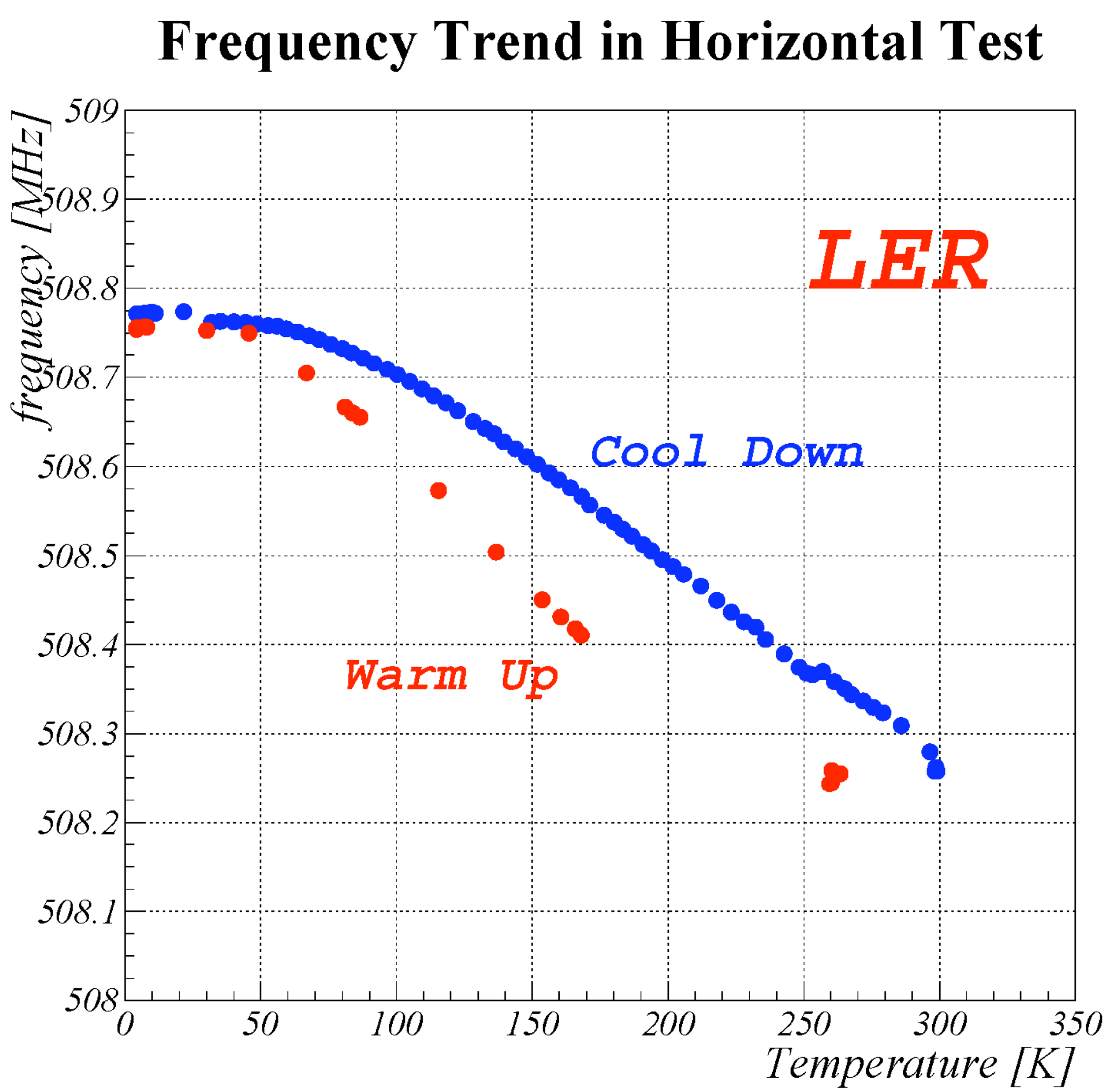
1.4 MV

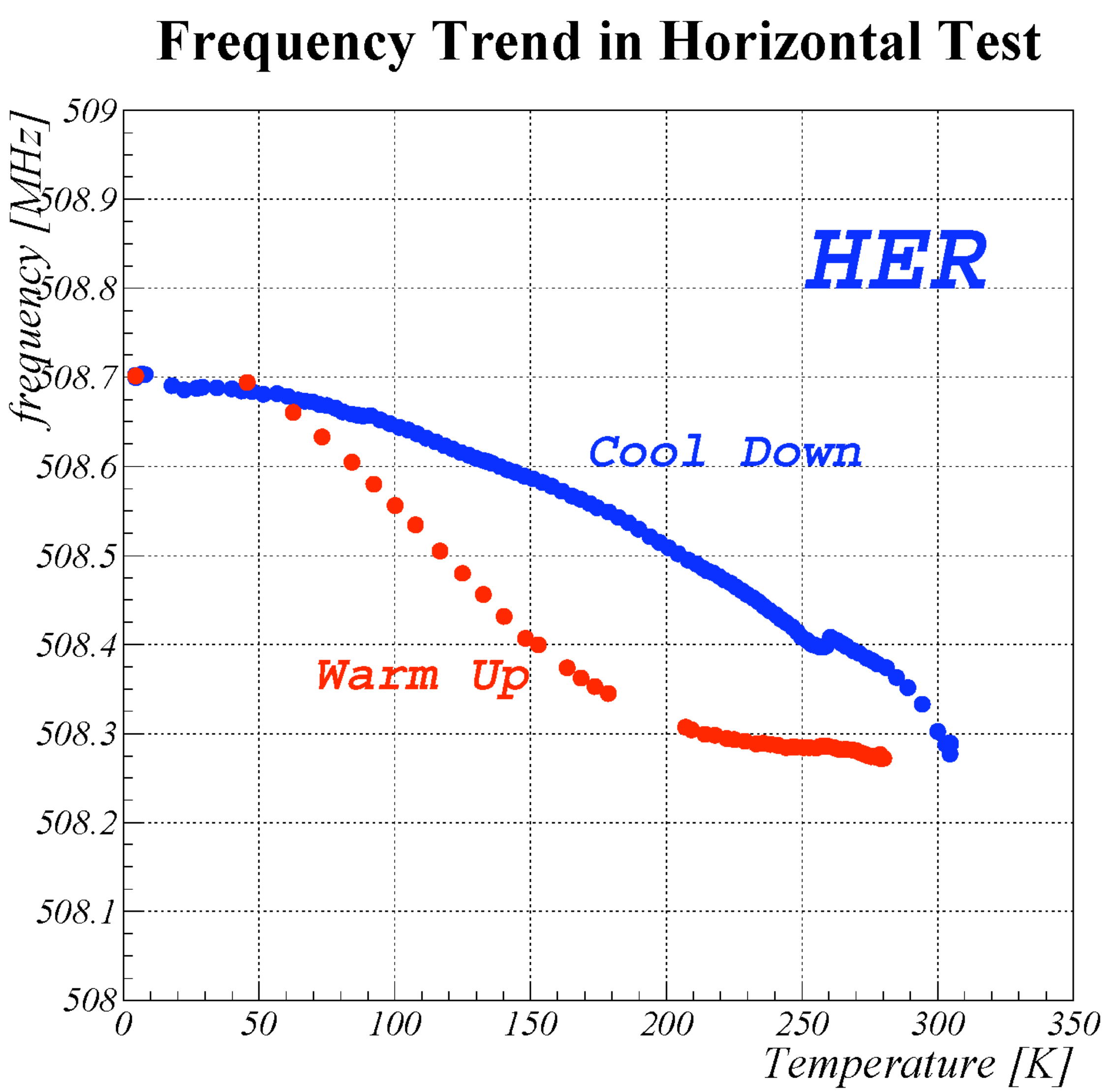


The sampling time is 0.5sec.

Frequency Trend in Horizontal Test

These figures show the results from the low power measurement by Network Analyzer.

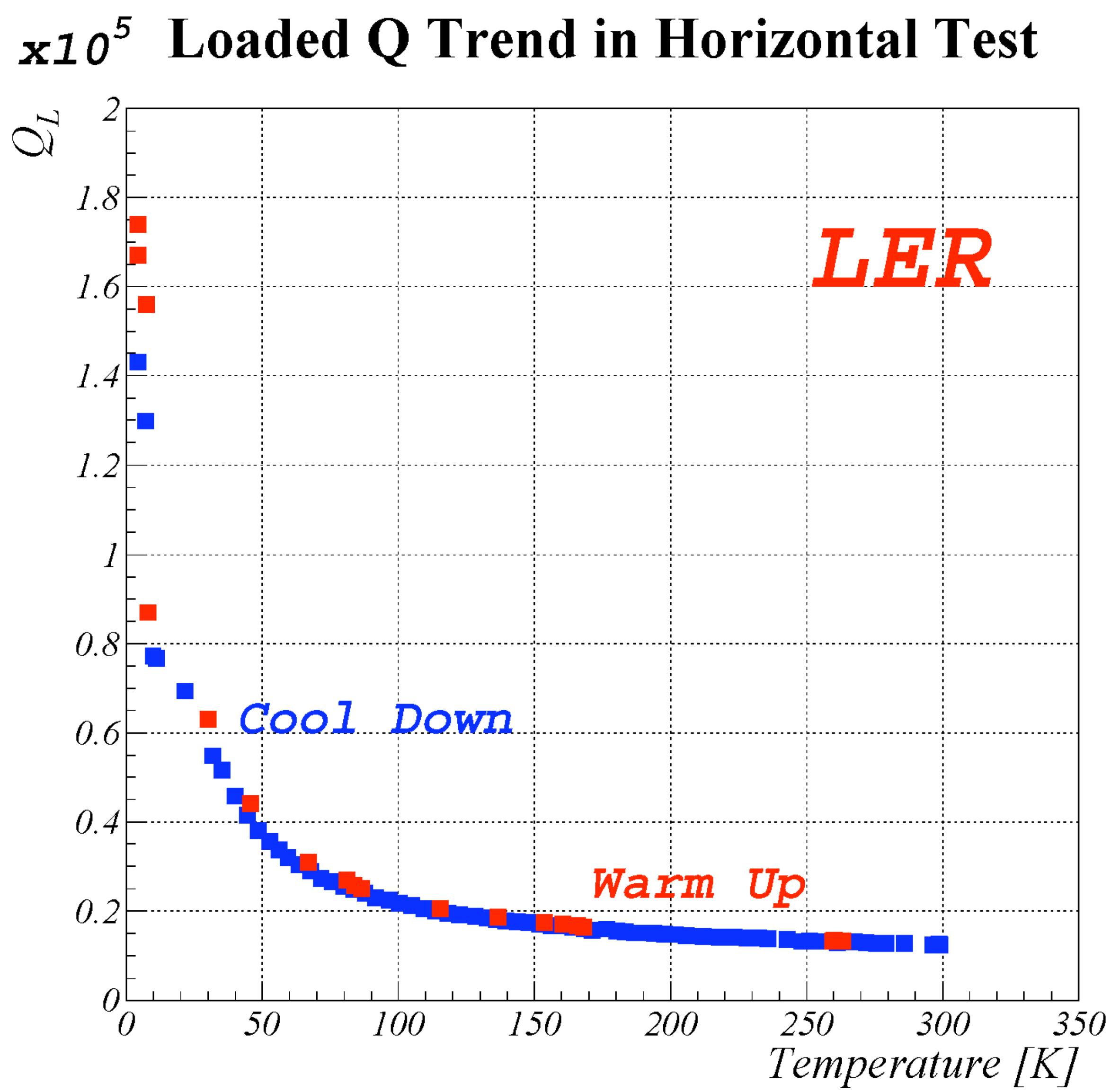


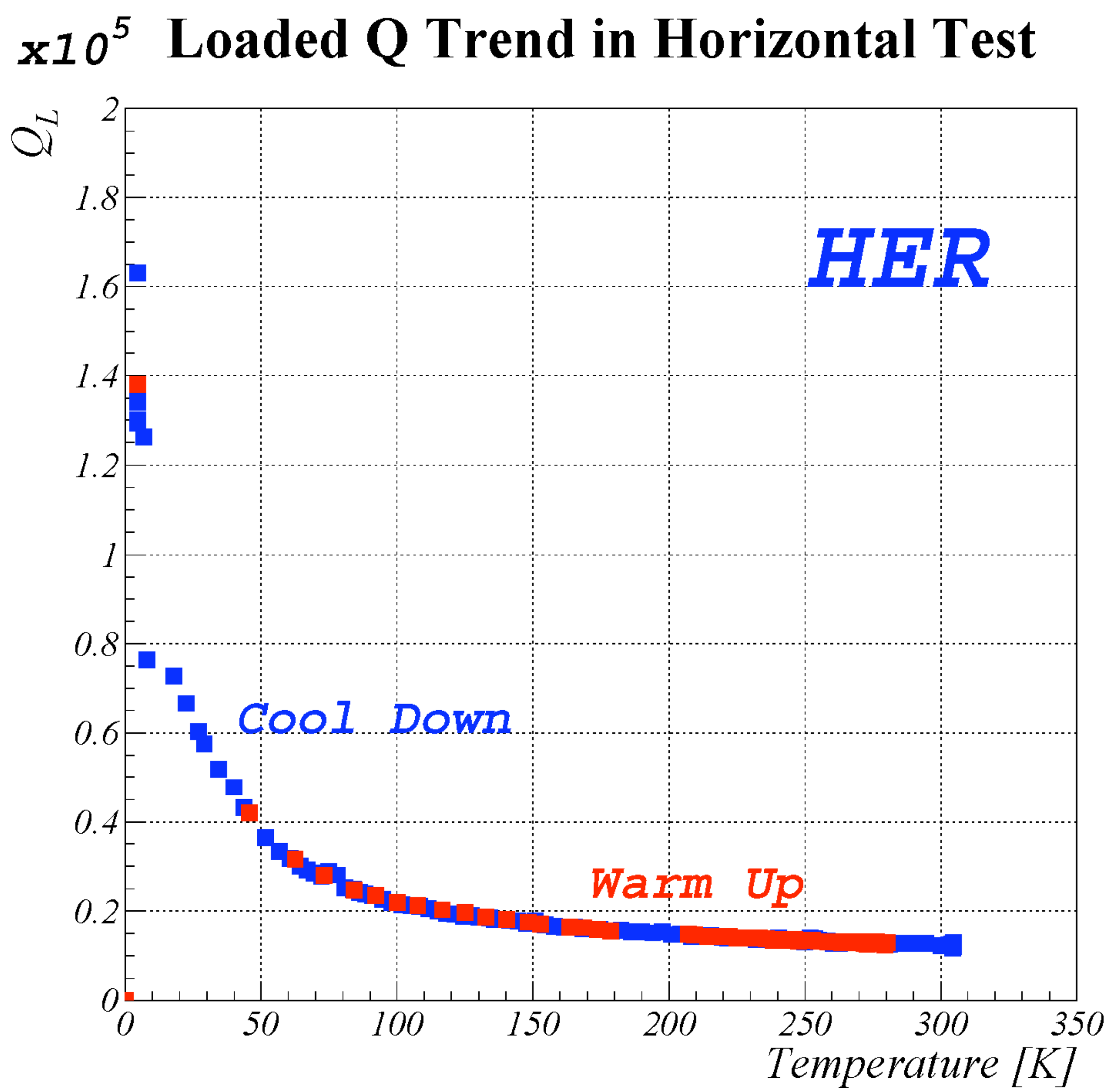


The cool-down were temporarily stopped due to the mode change for the refrigerator around 250K.

Q_L Trend in Horizontal Test

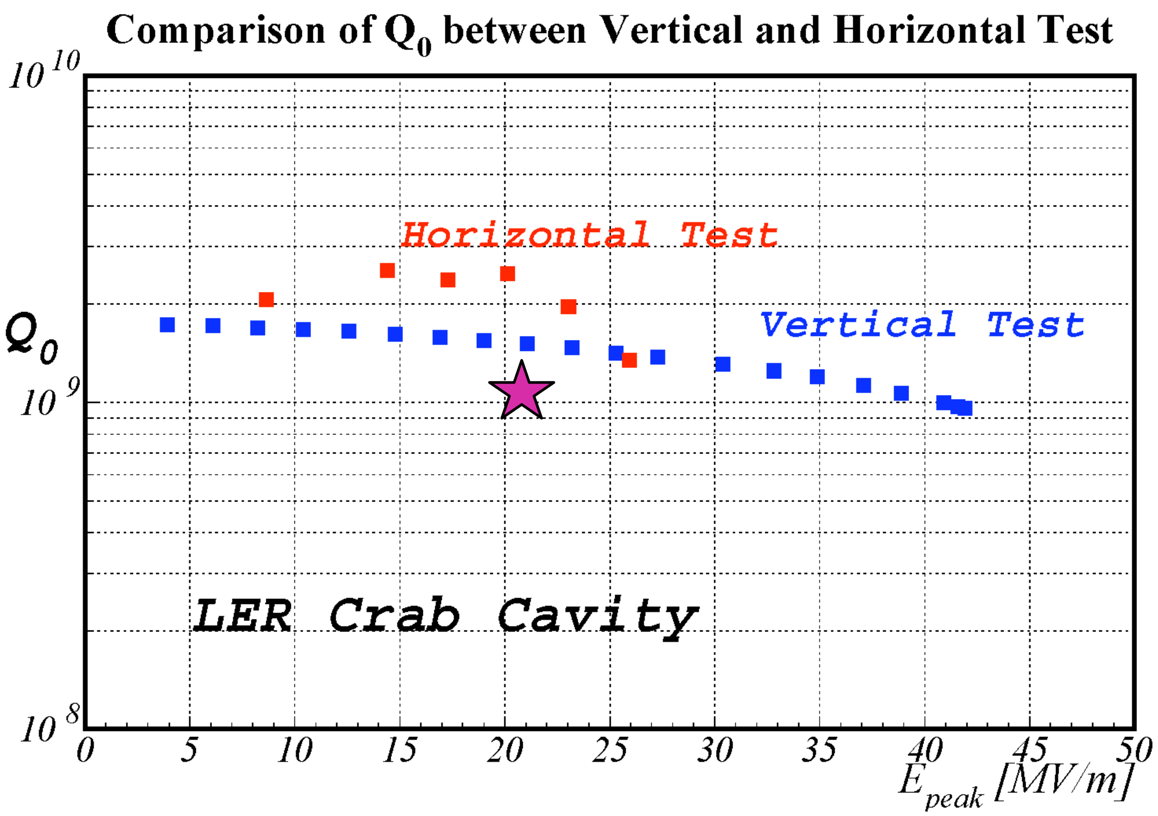
These figures show the results from the low power measurement by Network Analyzer.

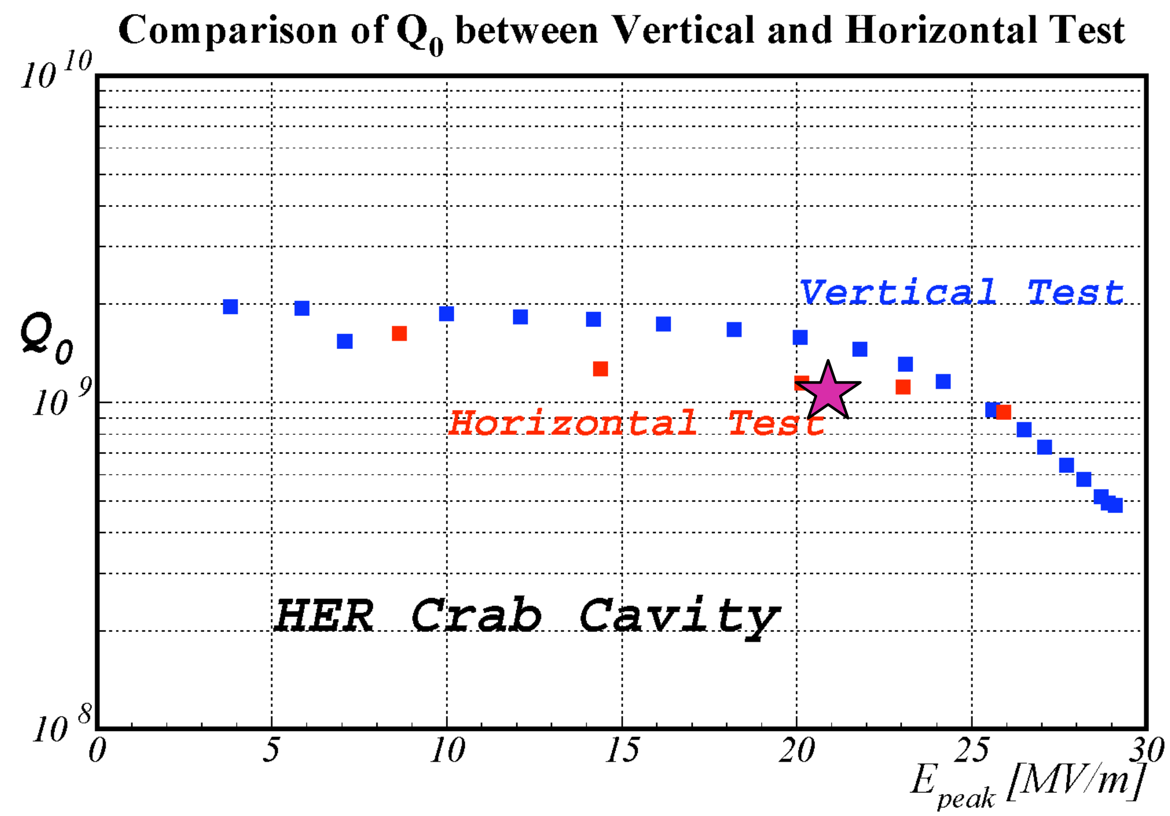




Q_0 vs. E_{sp} Curve

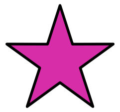
These figures show the comparison of Q_0 vs. E_{sp} curve between Vertical and Horizontal Test for the both Crab Cavities.



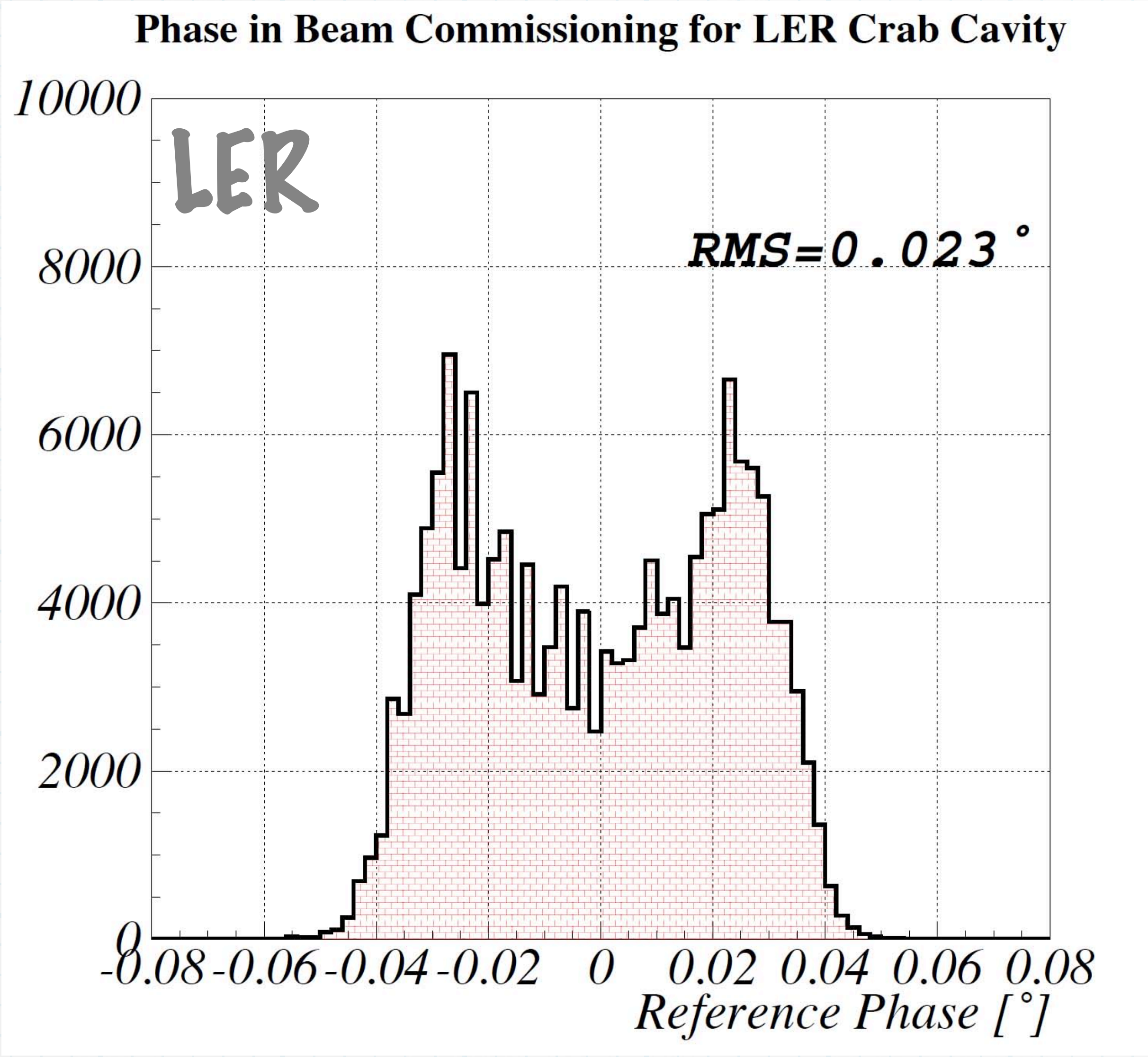


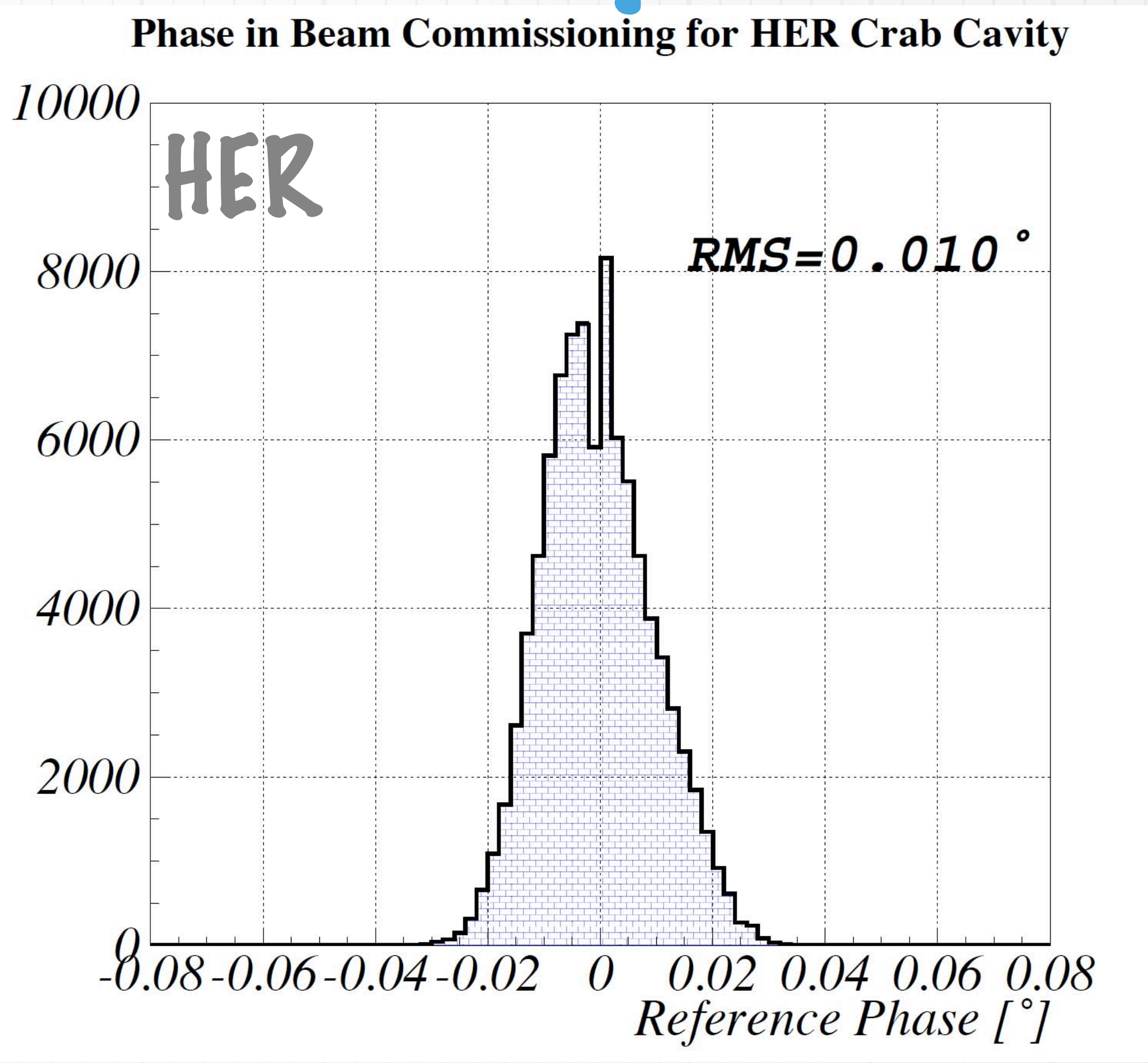
LER Crab Cavity

HER Crab Cavity

 shows the target value in the operation.

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.

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

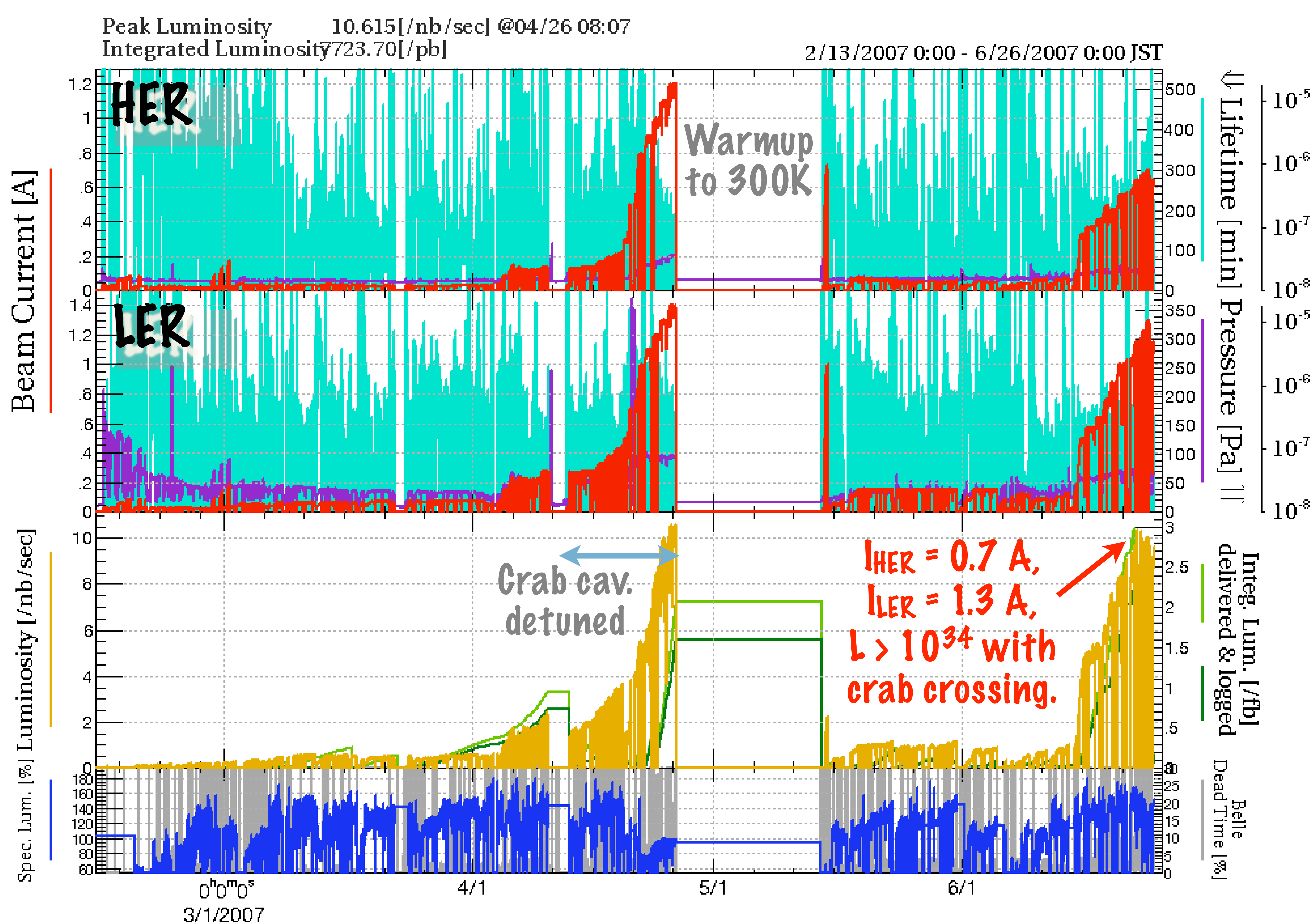
HER (e-, 8 GeV)

LER (e+, 3.5 GeV)

Crab Crossing Started at KEKB

First time in the world!

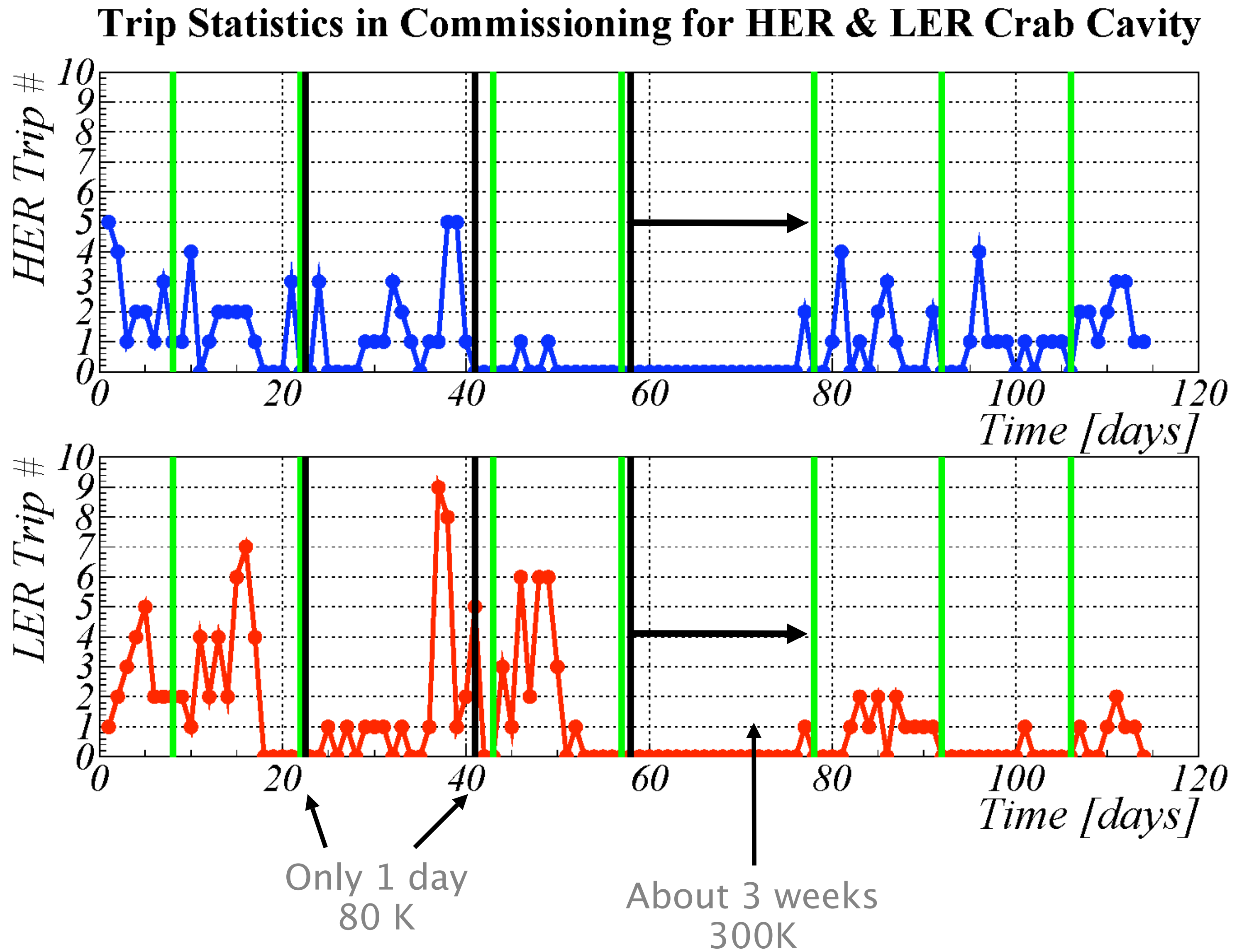
- A number of checks have confirmed the effective head-on collision:
  - streak camera
  - crab-phase scan
  - sign change and scan of crab voltage
  - horizontal beam-beam kick
  - vertical crabbing
- The highest vertical beam-beam tune-shift parameter is about 0.088 so far, which is higher than the 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
Crab cav. detuned
I_{HER} = 0.7 A,
I_{LER} = 1.3 A,
L > 10^{34} with crab crossing.
Beam Current [A]
Lifetime [min]
Pressure [Pa]
Luminosity [/nb/sec]
Integ. Lum. [/fb] delivered & logged
Spec. Lum. [%]
Belle Dead Time [%]
3/1/2007
4/1
5/1
6/1

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

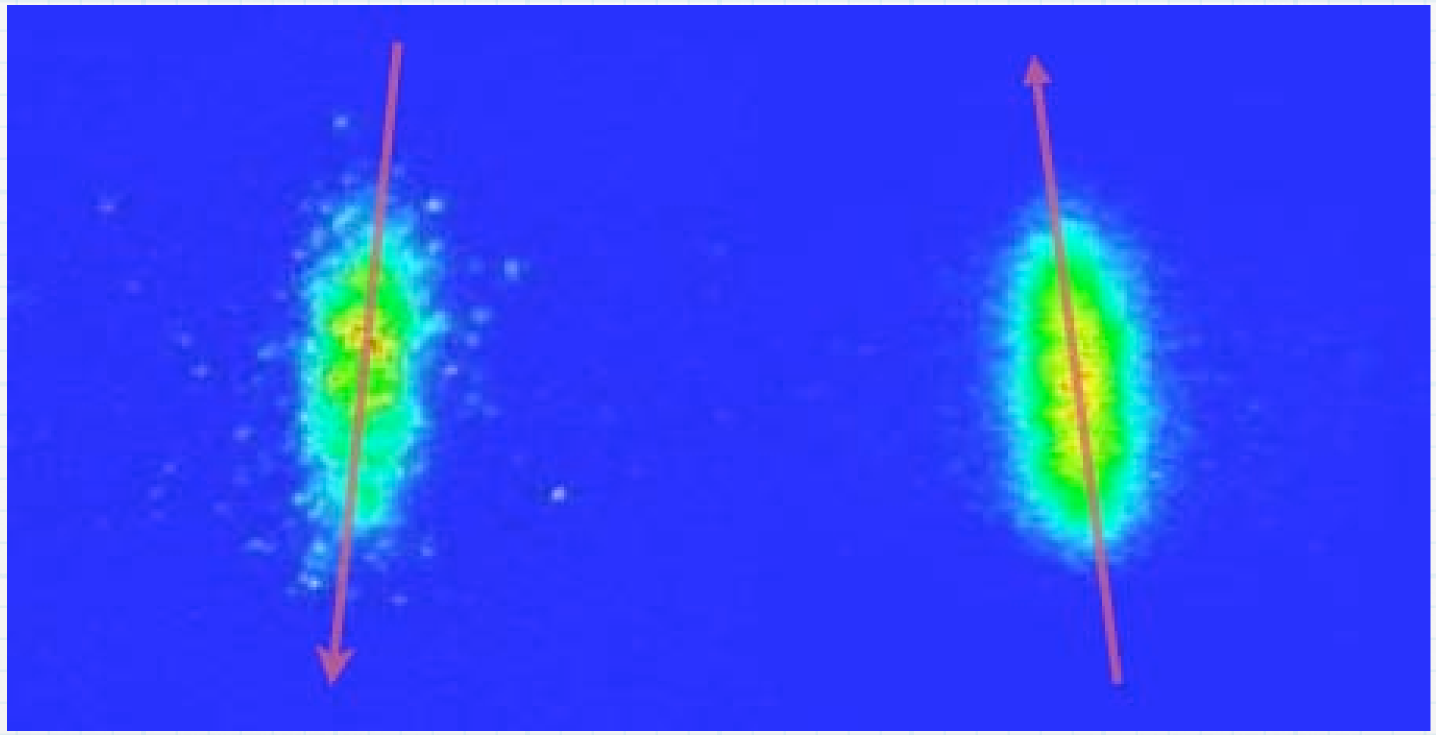
Beams has indeed tilted!

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

inside of the rings

outside of the rings

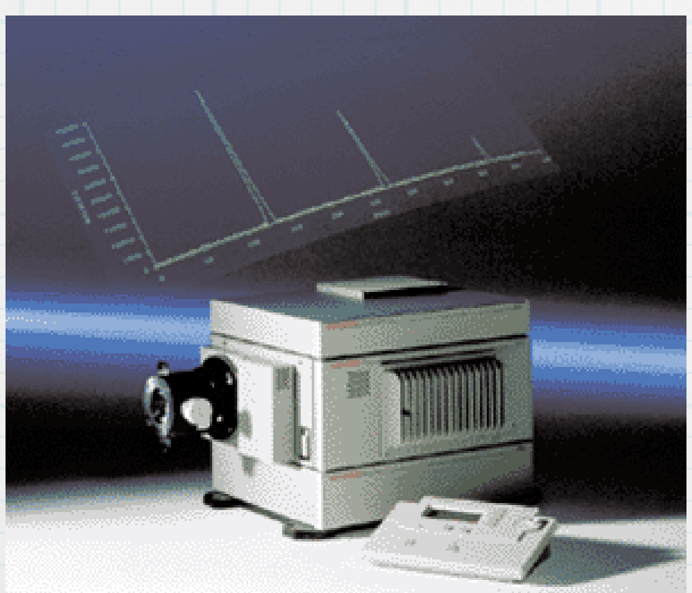
longitudinal



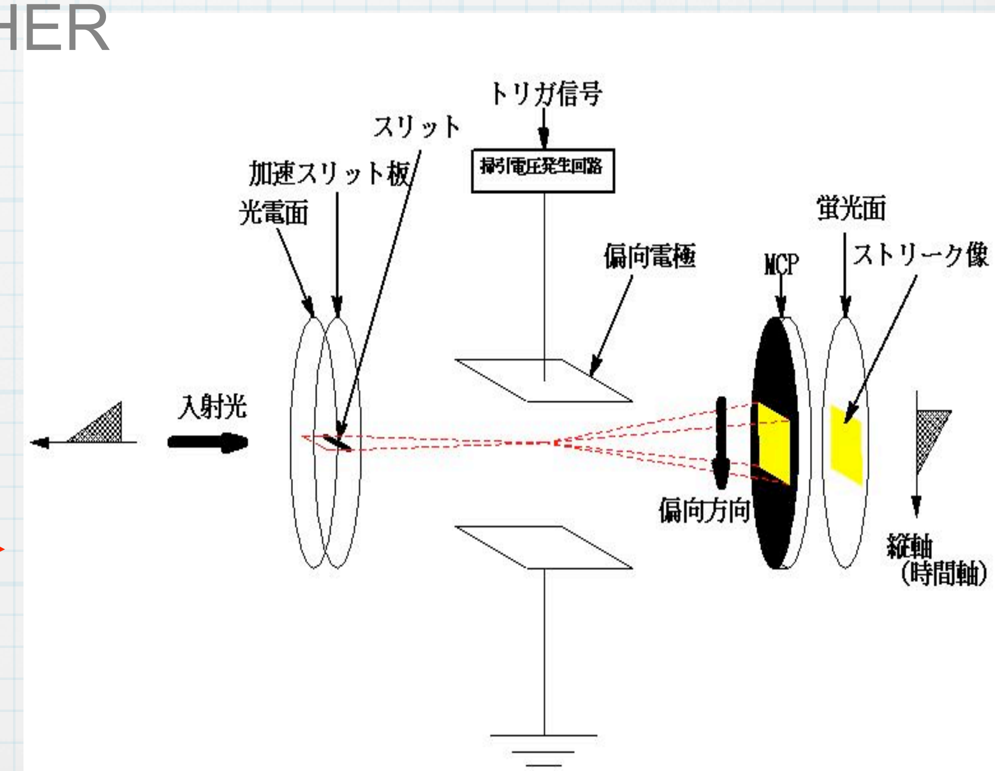
LER

HER

horizontal



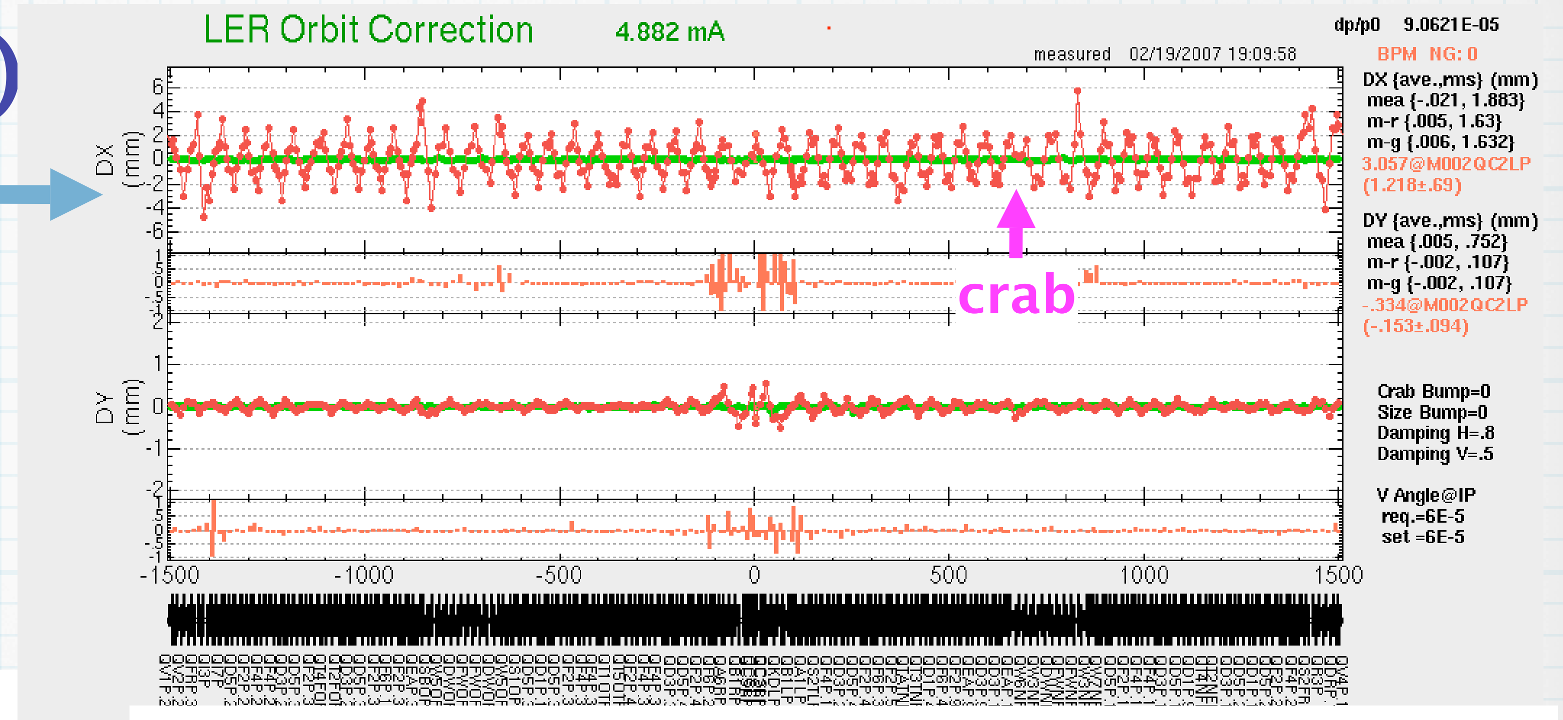
The streak camera

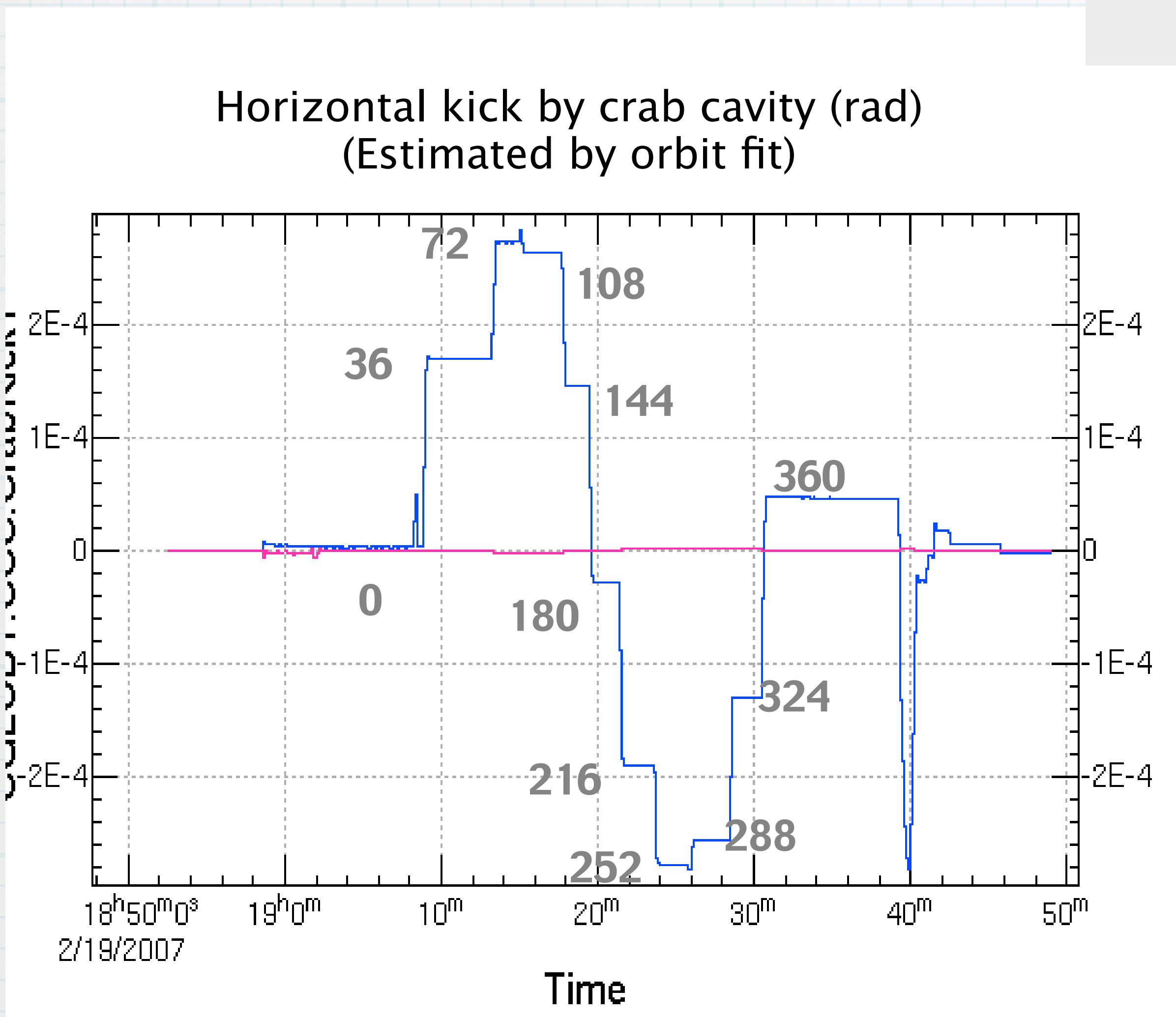


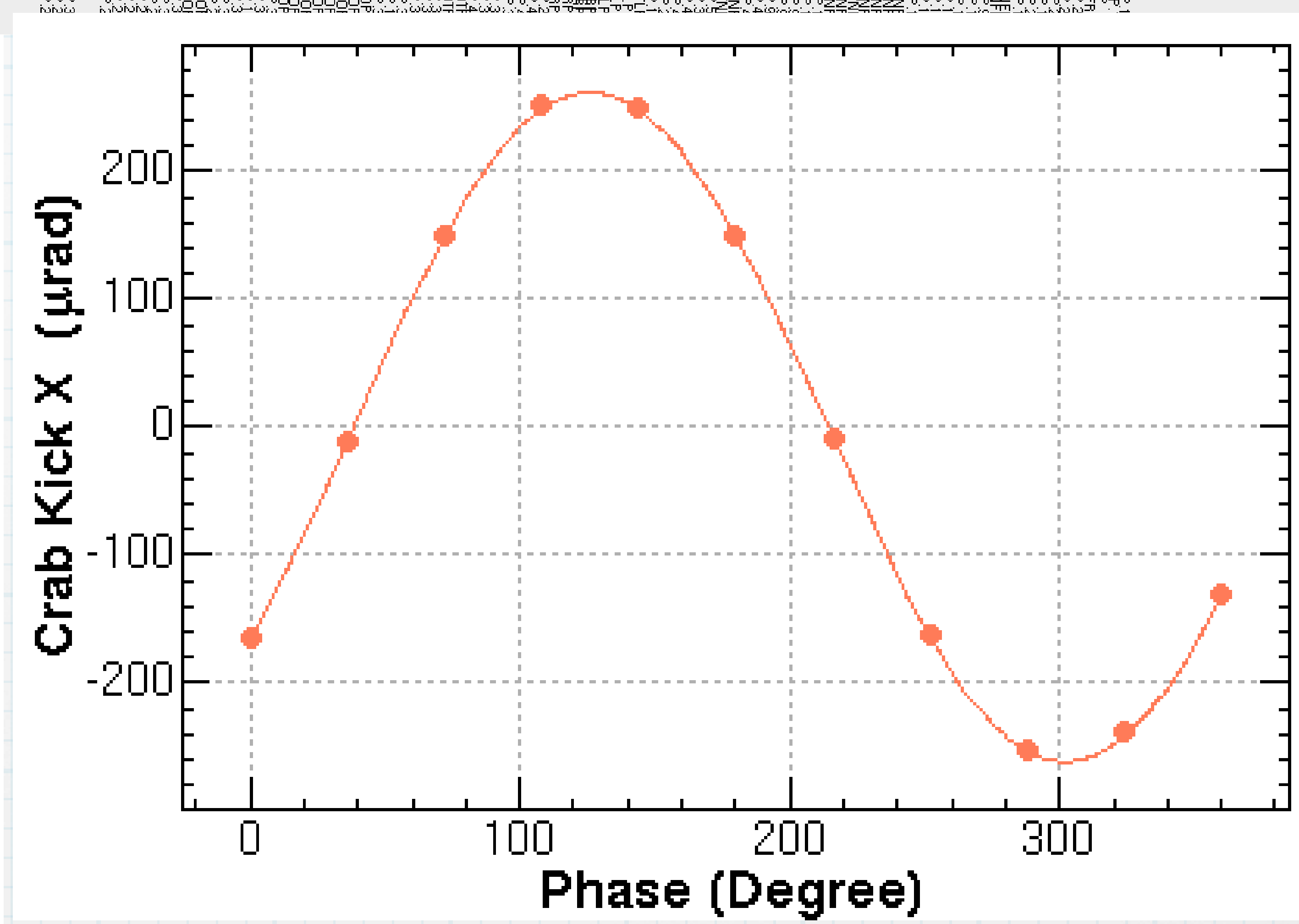
Crab Phase Scan (LER)

Horizontal orbit by crab kick

H. Koiso et al, TUPAN045



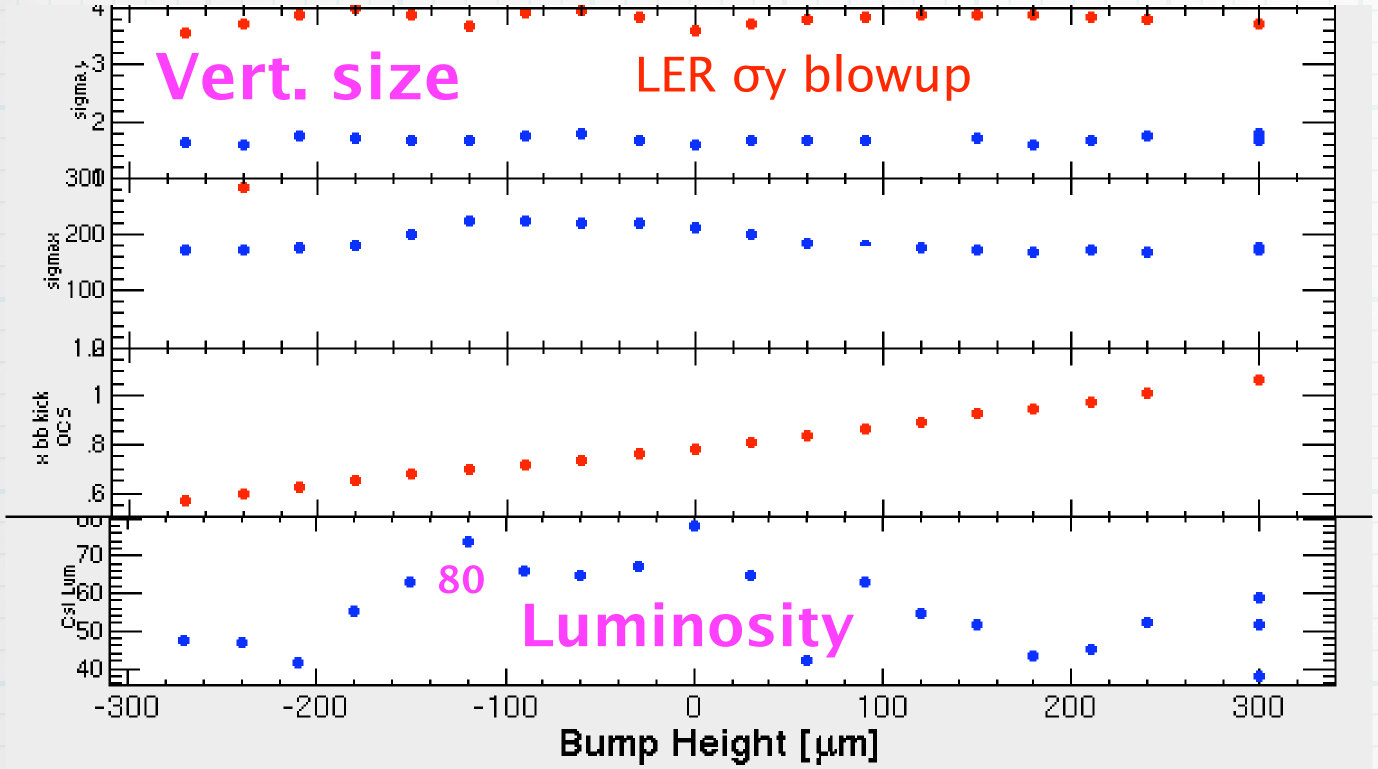


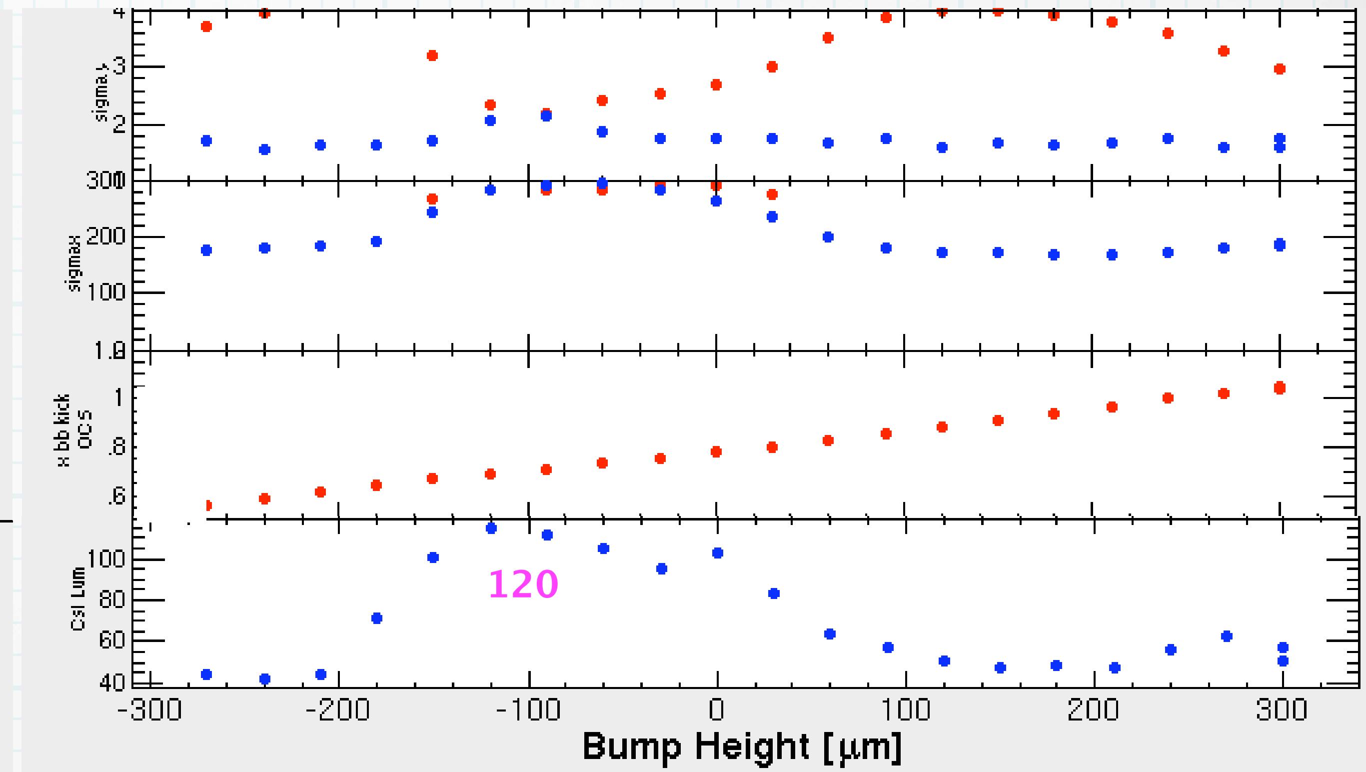


V_{crab} set:1.0MV, estimated: 0.987MV
agree to each other very well.

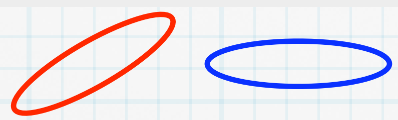
Sign Change in the Crab Angle

H. Koiso

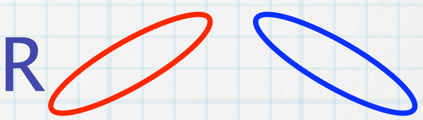


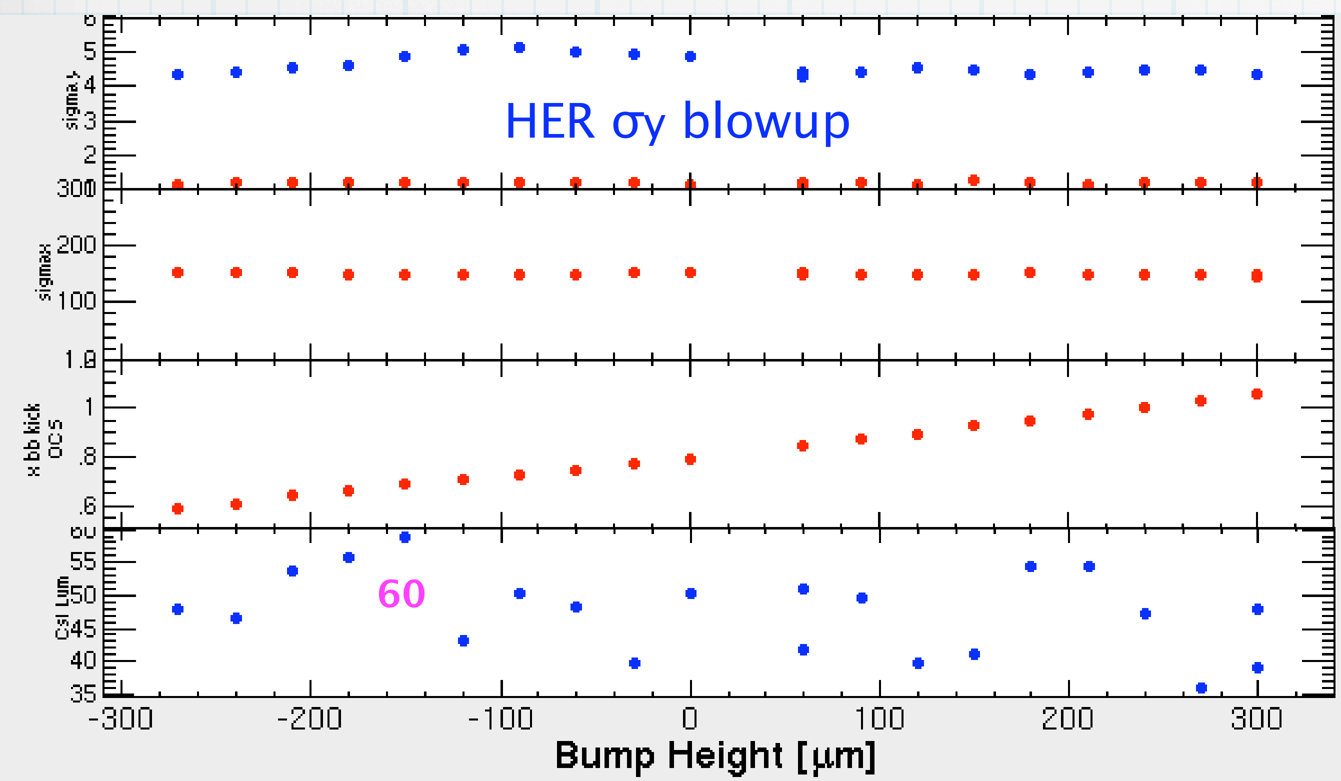


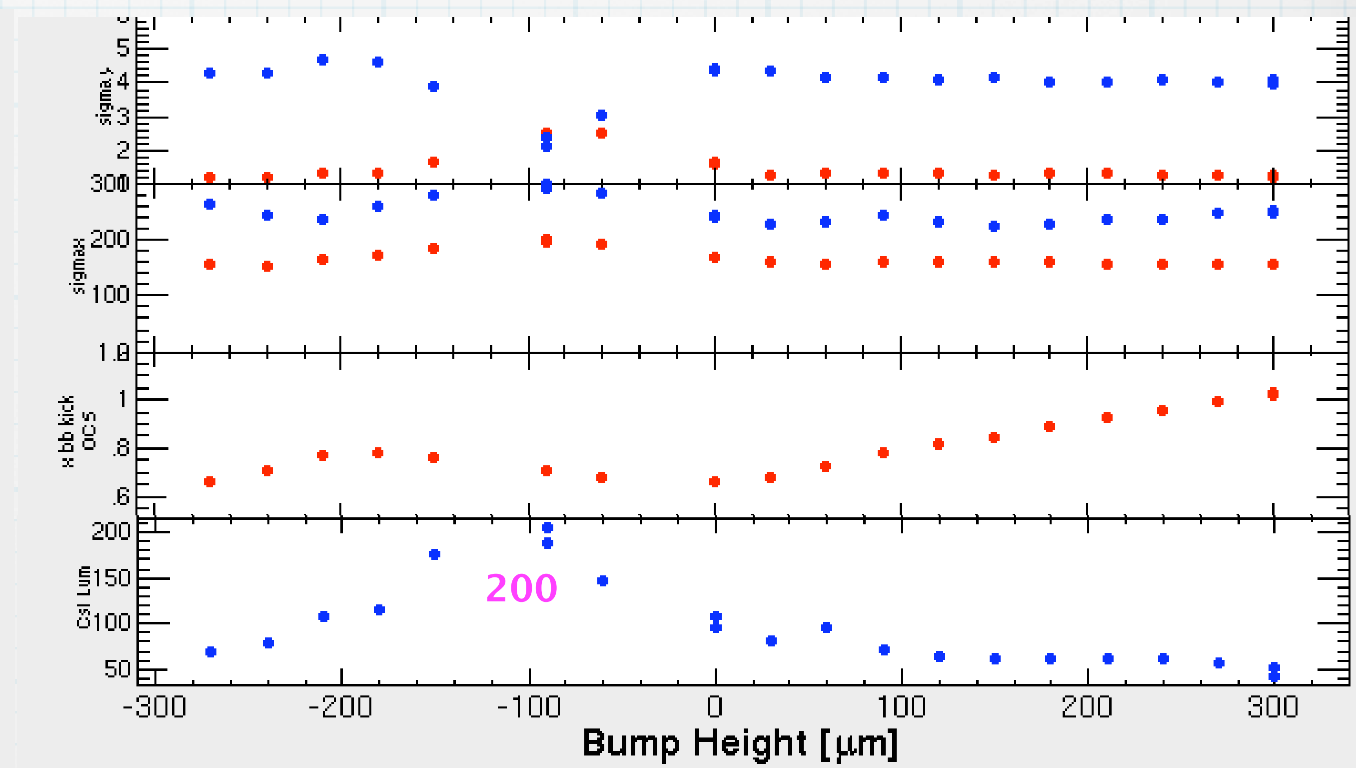
Reversed LER crab angle



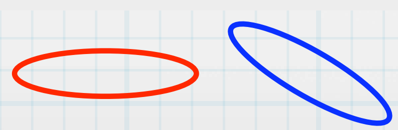
Reversed LER & HER



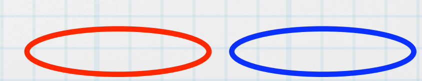




Reversed HER

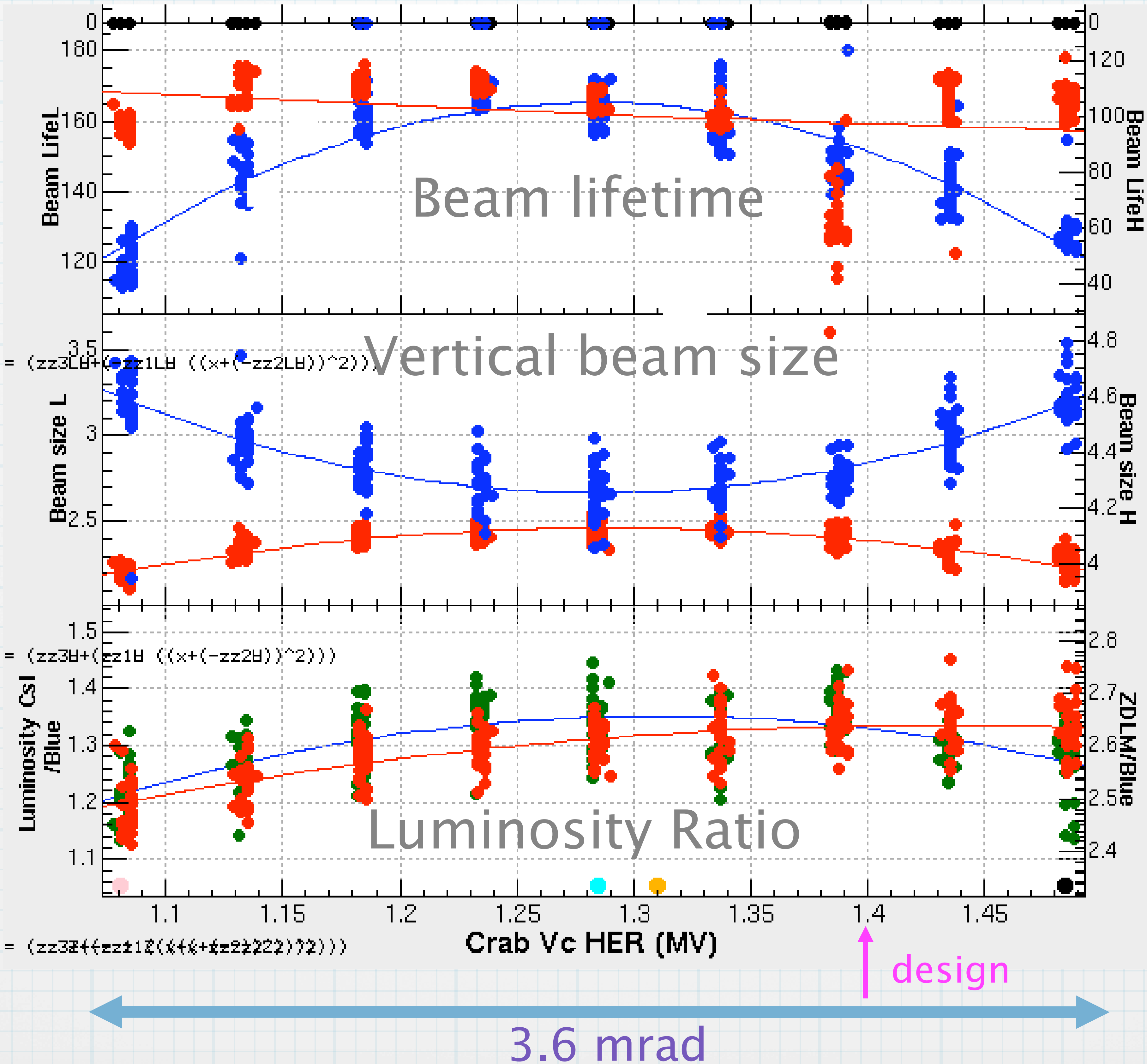


Both correct



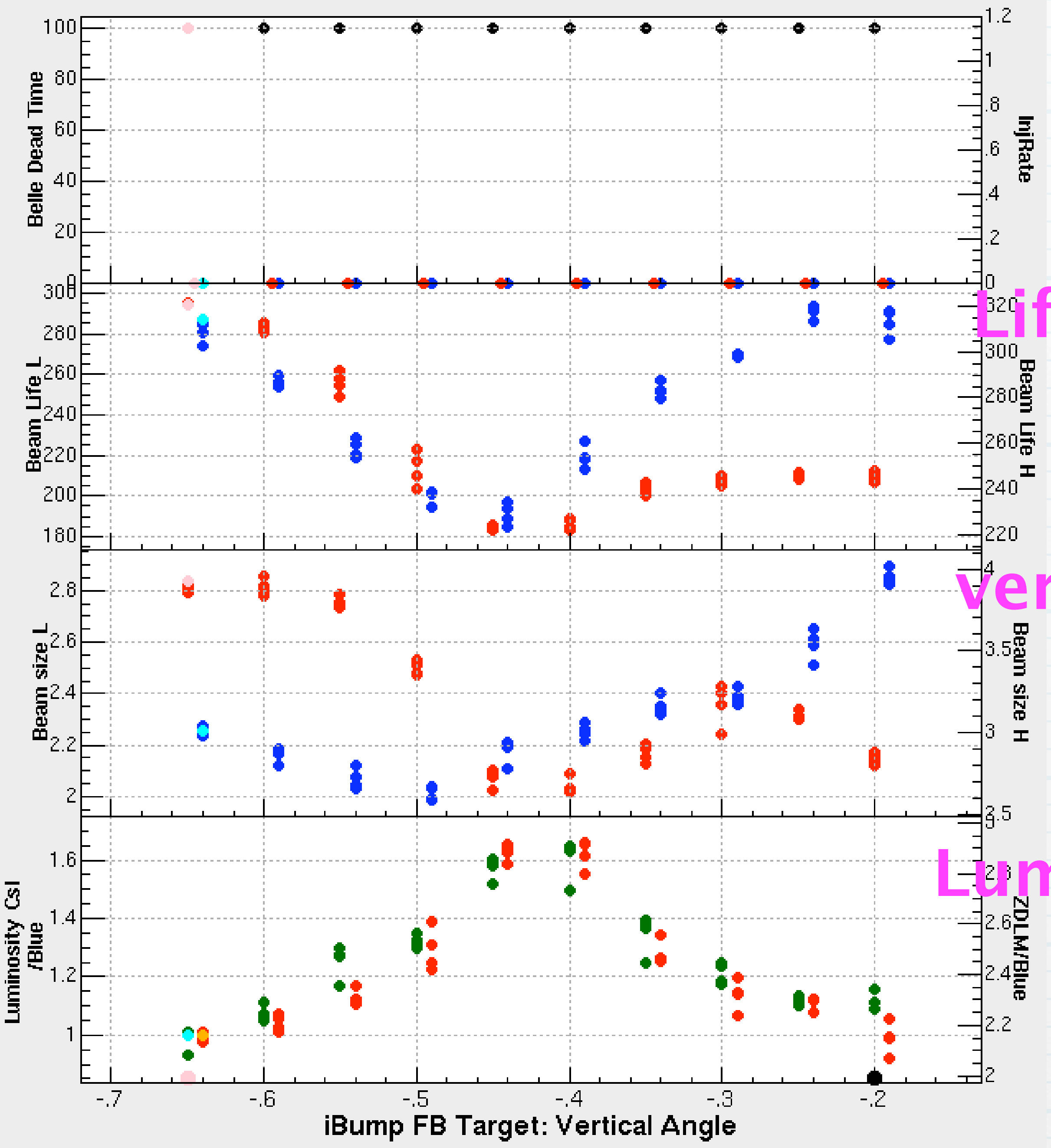
V_{crab} Scan (HER)

H. Koiso

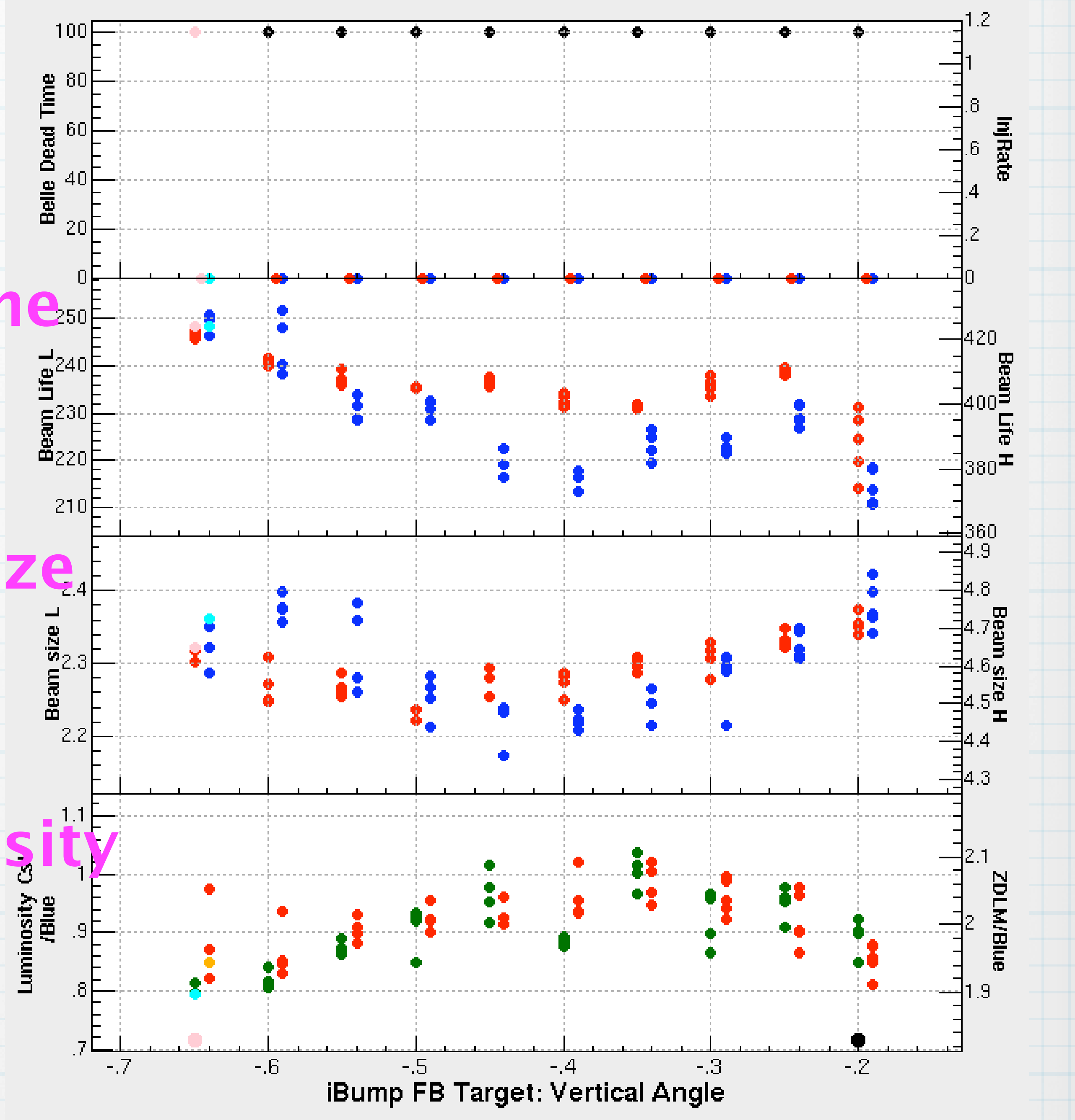


Vertical Crabbing ?

H. Koiso



asymmetric



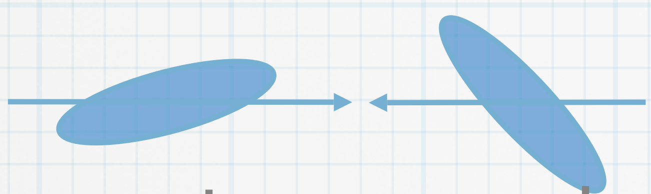
more symmetric

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

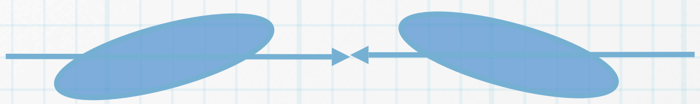
How to find out the vertical head-on condition

H. Koiso

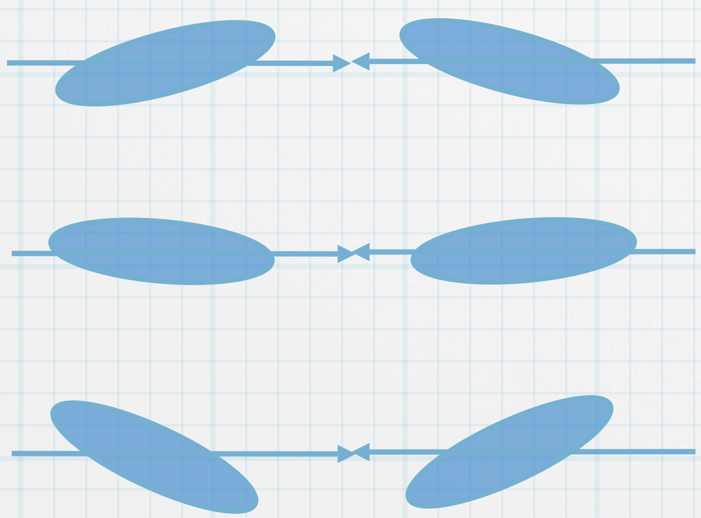
Adjust “R1” at the IP of one ring while fixing another to find out the head-on condition.



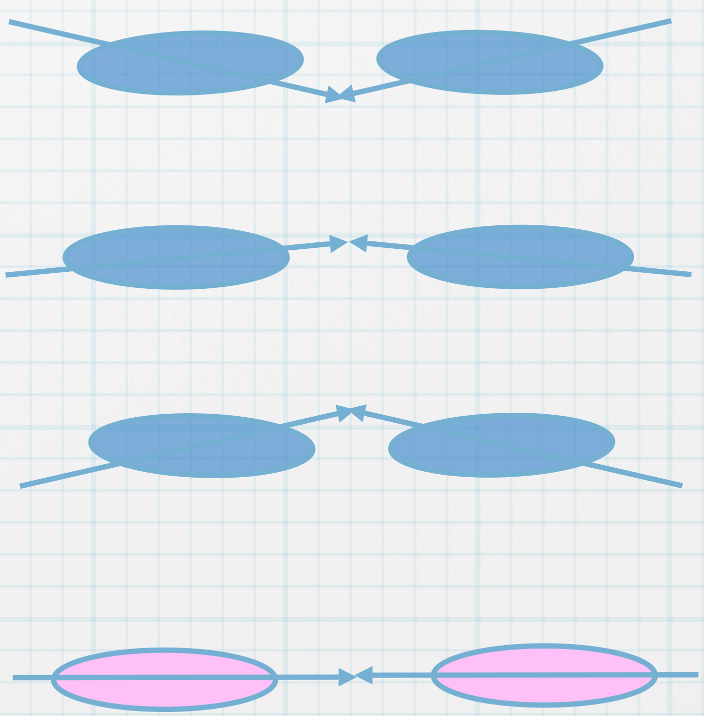
asymmetric: cannot become head-on by vertical angle.



symmetric: can become head-on by the vertical angle



Vertical angle scan



X-y coupling at the crab can affect the vertical crabbing also.

Specific Luminosity

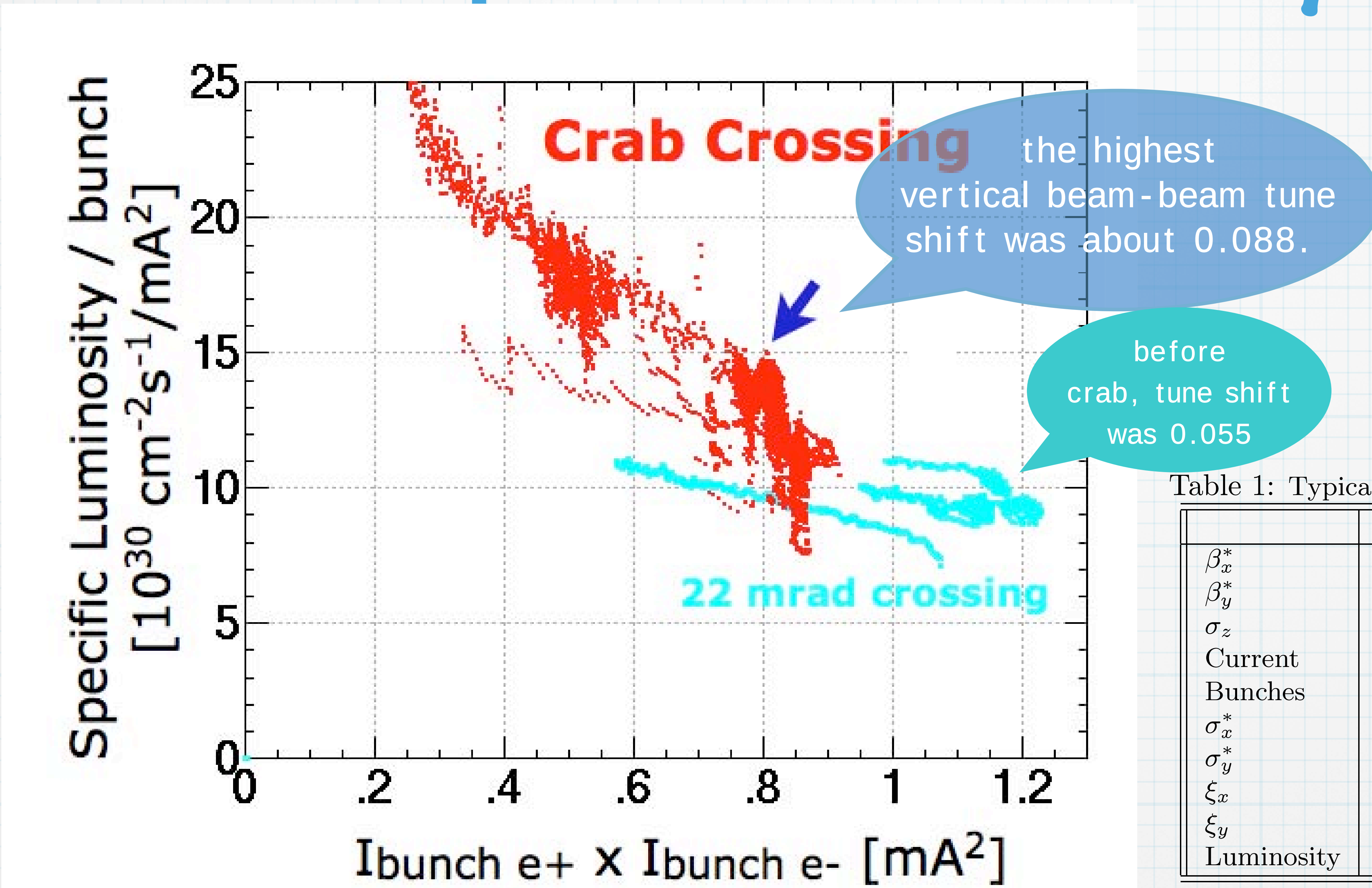


Table 1: Typical parameters for the crab crossing.

	LER	HER	
β_x^*	80	84	cm
β_y^*	0.59	0.65	cm
σ_z	~ 8	~ 6	mm
Current	60.9	33.3	mA
Bunches	50		
σ_x^*	120	140	μm
σ_y^*	1.3	1.3	μm
ξ_x	0.115	0.111	
ξ_y	0.108	0.088	
Luminosity	5.9		10^{32}cm^{-2}s^{-1}

- 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 by about 15% more than the geometric gain.
- Need more time to achieve the goal (X2 specific luminosity).

Issue 1: Too many tuning knobs?

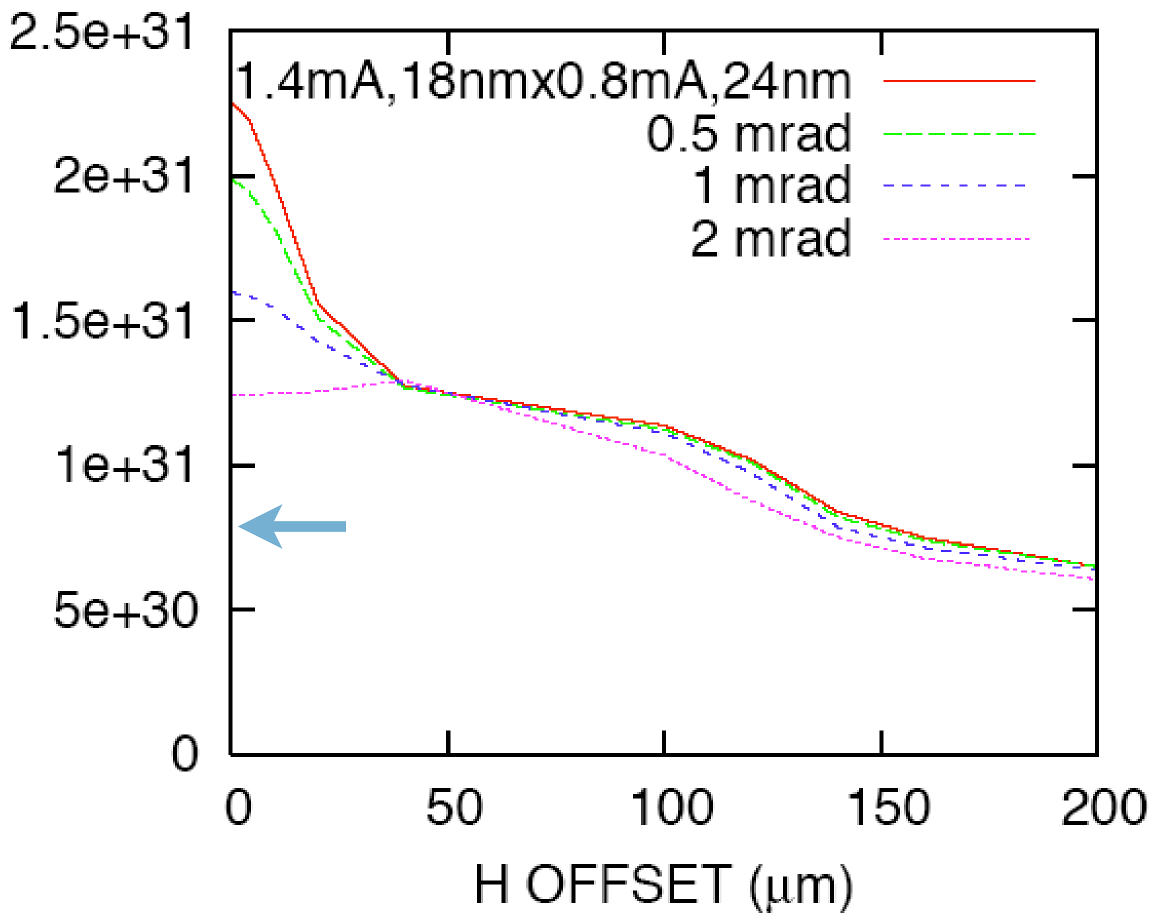
Table 3: Tuning knobs for the crab crossing and their observables. Many depend only on the beam size σ_y at the synchrotron radiation monitor (SRM), besides the luminosity $\mathcal{L}$.

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

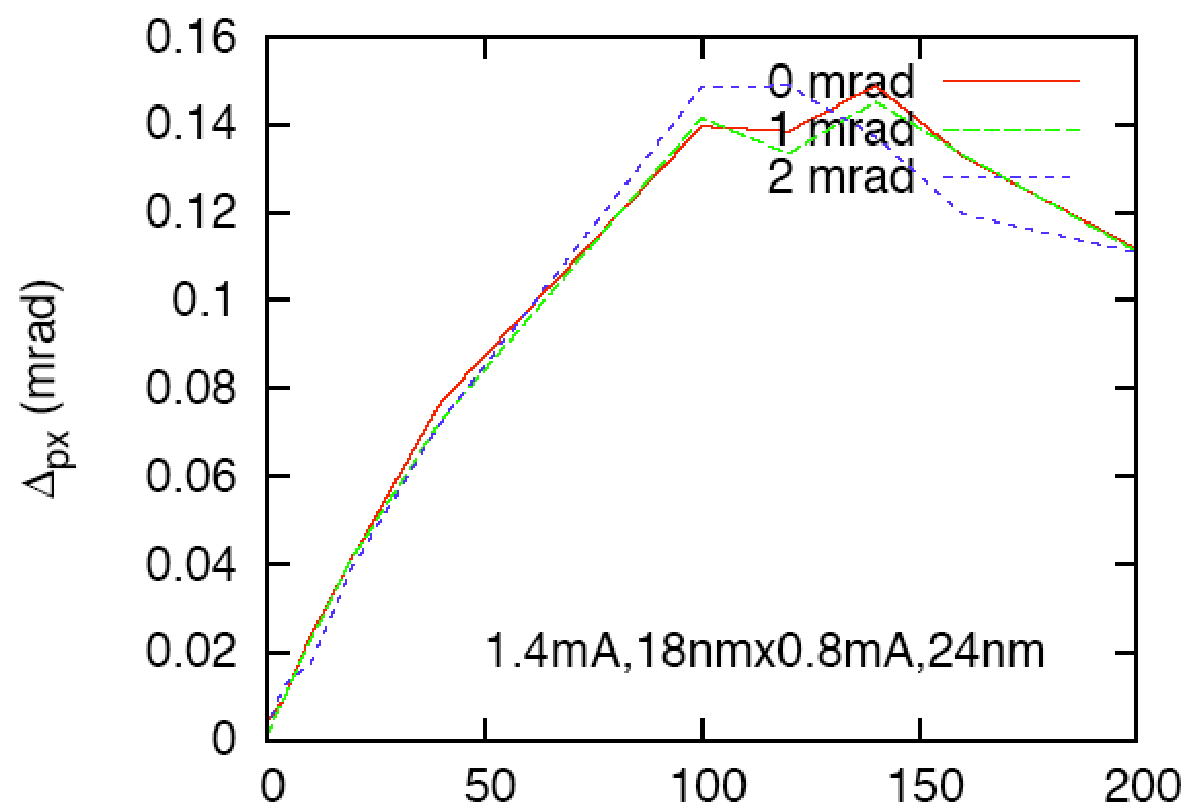
- Many knobs are determined by scans only on the luminosity, beam sizes, and the lifetime.
- Scan is slow, each takes about 30 minutes.
- Question in the multi-dimensional nonlinear optimization.

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

- Luminosity



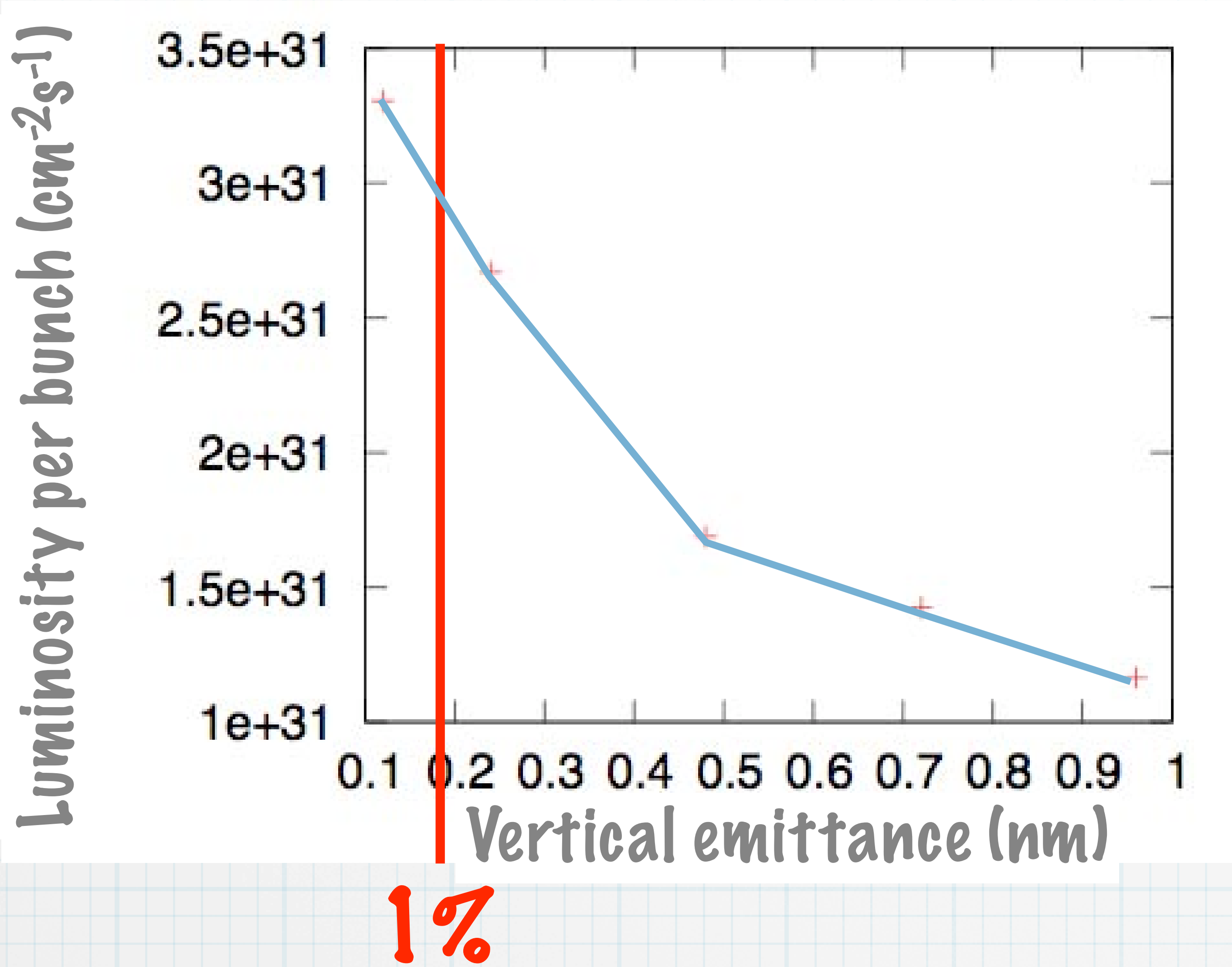
beam-beam kick



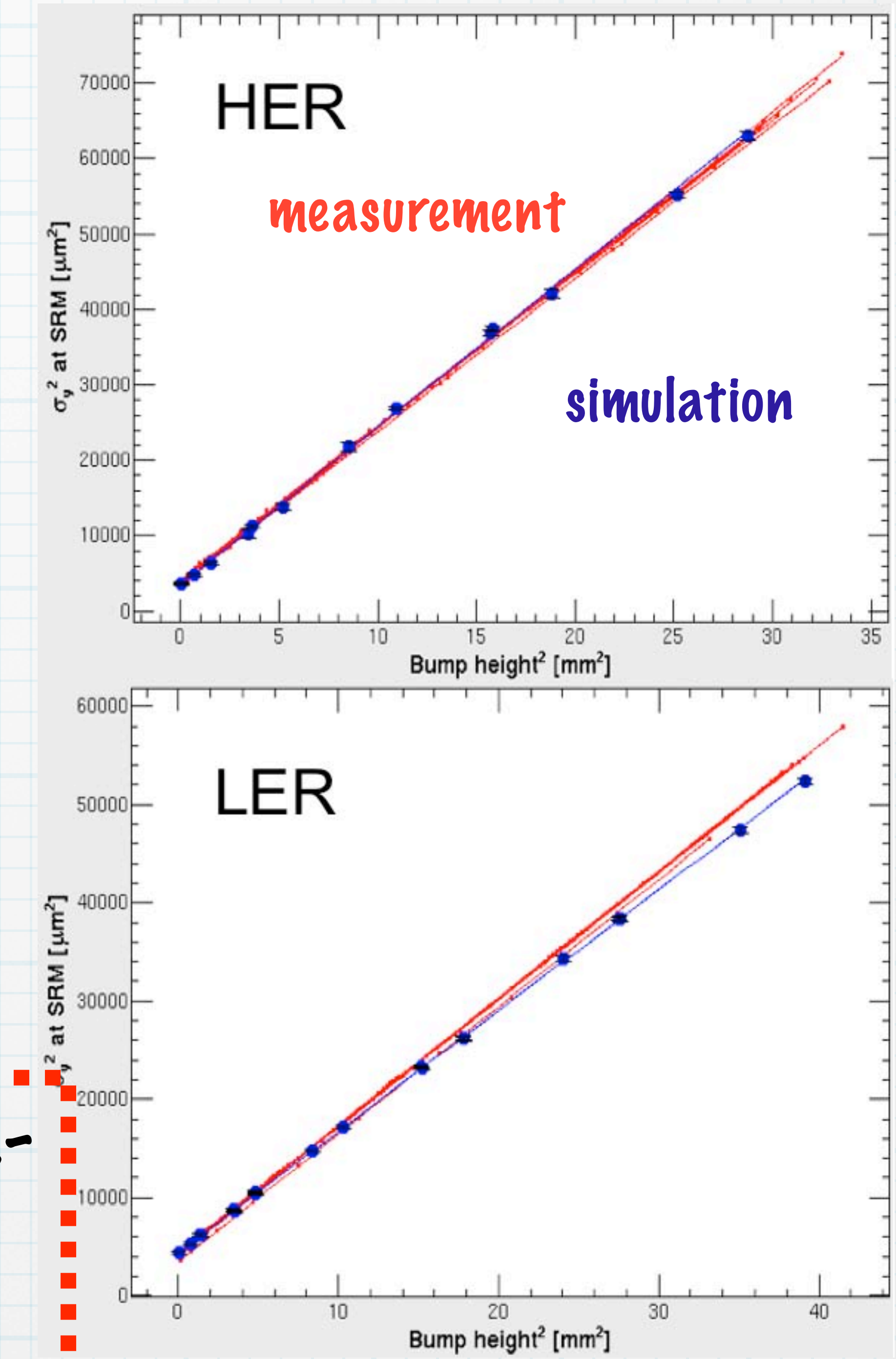
K. Ohmi

- 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.

Issue 2: Vertical emittance small enough?



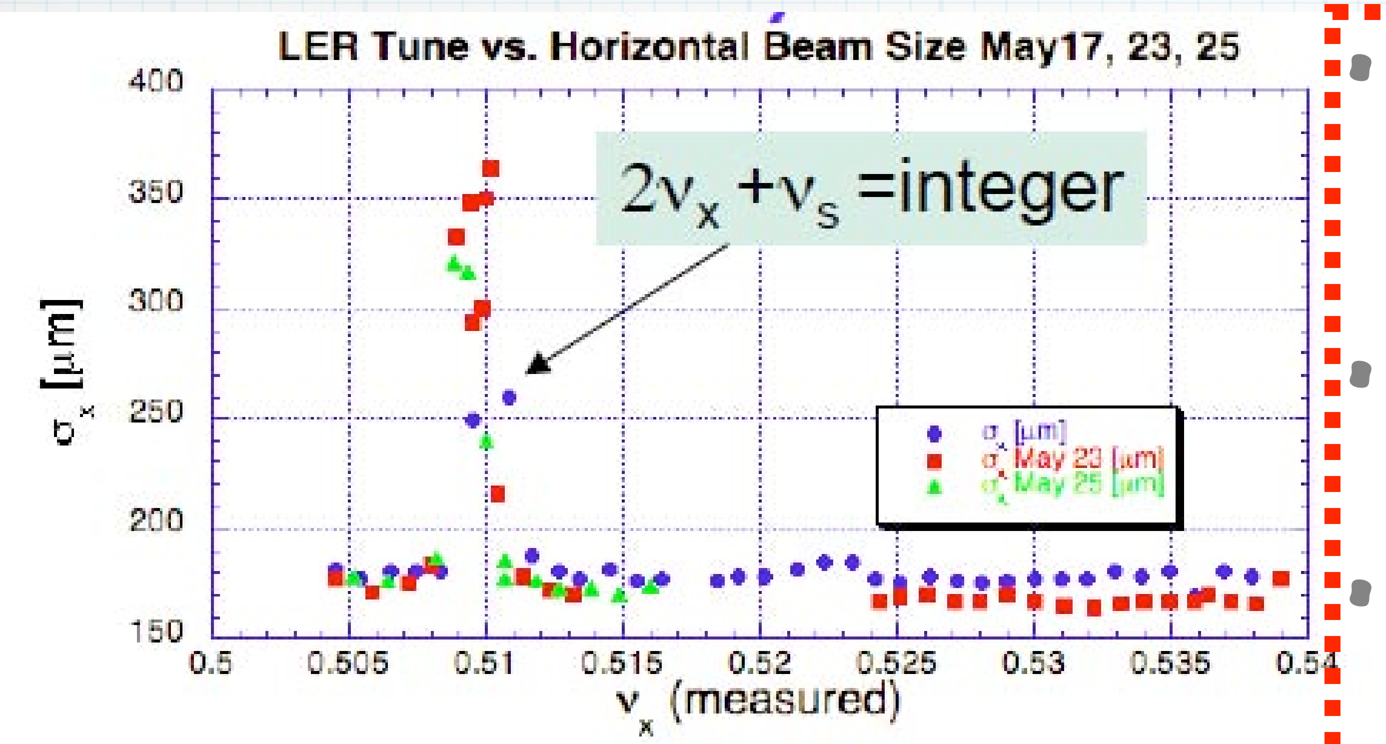
K. Ohmi



N. Iida et al, TUPAN042

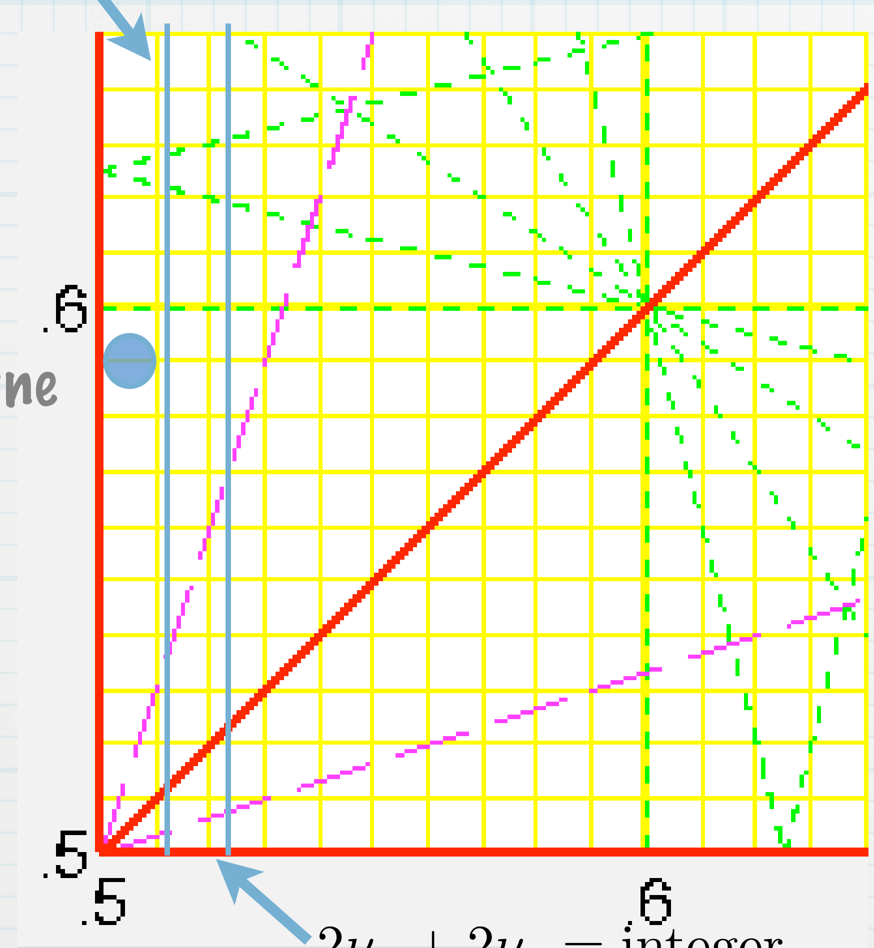
- According to the simulation, the vertical single-beam emittance must be less than 1% to achieve the high luminosity(above).
- Recent calibration of the size monitor with "iSize" bump orbit shows the emittance ratio was 1.4%/1.2% for LER/HER (right).

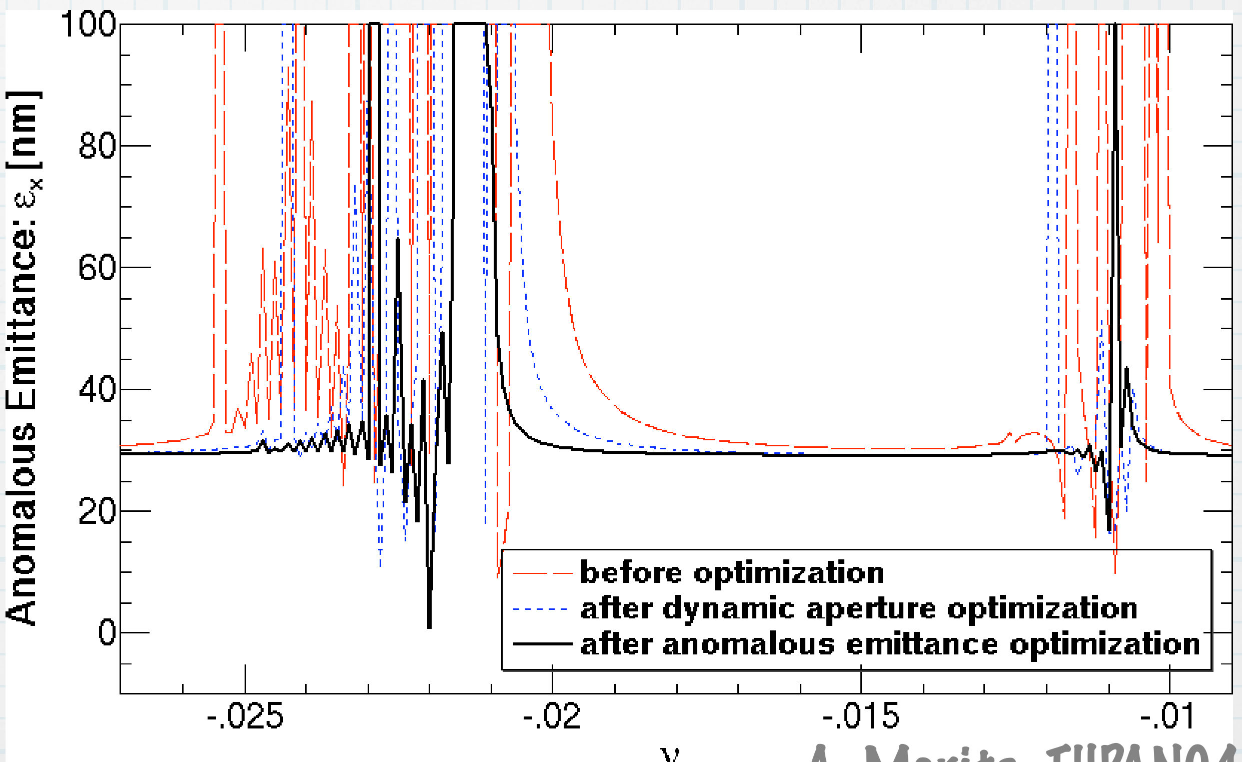
Issue 3: Synchrotron-betatron resonance



Y. Funakoshi, TUPAN041

- 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).





A. Morita, THPAN042

More Issues

- The LER solenoid was turned off to make the optics closer to the model, but no clear effect was seen on collisioin.
- A negative momentum compaction lattice was tried to mitigate the synchrotron-betatron resonances, but a microwave single-bunch instability was seen in the LER for Ib > 0.6 mA, so it was given up.
- The dynamic emittance blowup due to beam-beam effect, and its dilution to the vertical, is not a problem if the x-y coupling at the IP is corrected.
-

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.
- No clear reason was confirmed why the luminosity did not reach the predicted value.
- Needs more time to reach the high luminosity predicted by simulations.