Crab Cavity Operation

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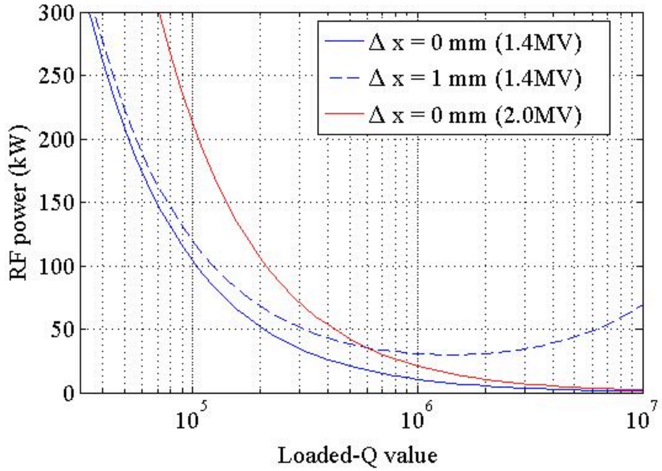
Crab RF system_1

The required RF power to maintain the crabbing voltage is given as:
(for a simple case of β>>1, crab phase=π/2, and loading angle =0)

$$P_g = \frac{1}{4\left(\frac{R_\perp}{Q_0}\right)Q_L}\left\{V_c + I_b\left(\frac{R_\perp}{Q_0}\right)Q_L k\Delta x\right\}^2$$



Dependence of RF power on the loaded Q value and a horizontal beam orbit for a beam current of 2 A.

- We have chosen Q_L=1~2 x10^5 for a good compromise.
  - This value is suitable for operating the system with a possible error of ΔX=1mm, and
  - A high power source of 200 kW is sufficient for conditioning the cavity up to 2 MV.

Typical parameters for the crab crossing.

Table 1: Parameters for the crab crossing for KEKB.

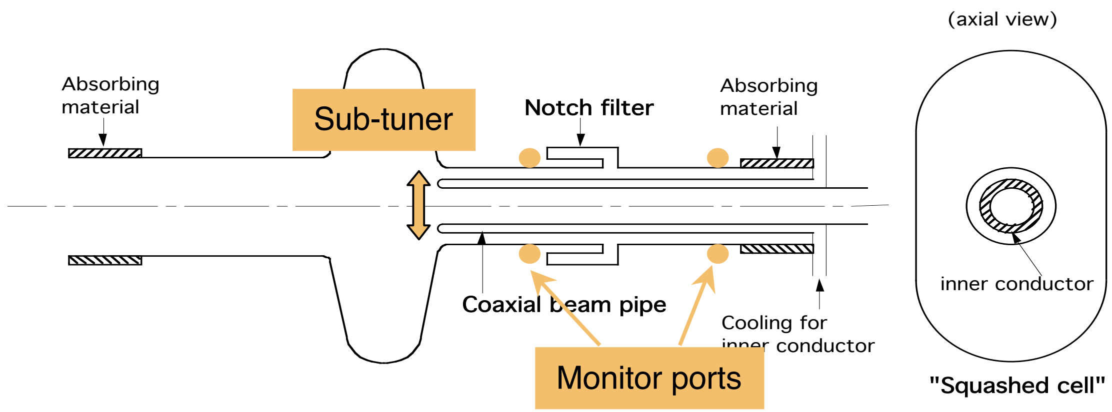
	LER	HER	unit
Beam energy	3.5	8.0	GeV
Beam current	1.7	1.35	A
RF frequency	508.9		MHz
Crossing angle	$\pm$11		mrad
$\beta_{x,IP}$	80	80	cm
$\beta_{x,crab}$	80	170	m
V_{kick}	0.9	1.45	MV
Loaded-Q	2.0×10^5	1.6×10^5	
RF power for V_{kick}	23	90	kW

Crab RF system_2

- Two new RF stations, each for one crab cavity, were constructed in the D11 building.
  - Two reused klystrons that have been tested up to 600 kW were set.
  - The high-power system and most of the low-level RF system are similar to those of the SC accelerating cavity stations.
  - Conventional amplitude and phase feedback loops are used to control the cavity field and the klystron output.
  - The resonant frequency of the cavity is controlled by the main tuner system consisting of a motor and piezo element, which moves the coaxial beam pipe in the longitudinal direction with respect to the cavity cell.
  - The interlock system includes a quench detector, arc sensors at the input coupler, vacuum pressure gauges, temperature sensors, etc.

Crab RF system_3

- Special cares are taken for the coaxial beam pipe.
  - A sub tuner is added to align the coax horizontally in order to minimize the coupling of the crabbing mode between the cell and the coax.
  - RF signals monitored at seven pickup ports located in the coax are connected to the fast interlock system. It protects the ferrite damper at the end of the coax from abnormally large crabbing-mode power that can leak through the coax on the occasion of a discharge at the coax or the notch filter.



Squashed Crab cavity for B-factories

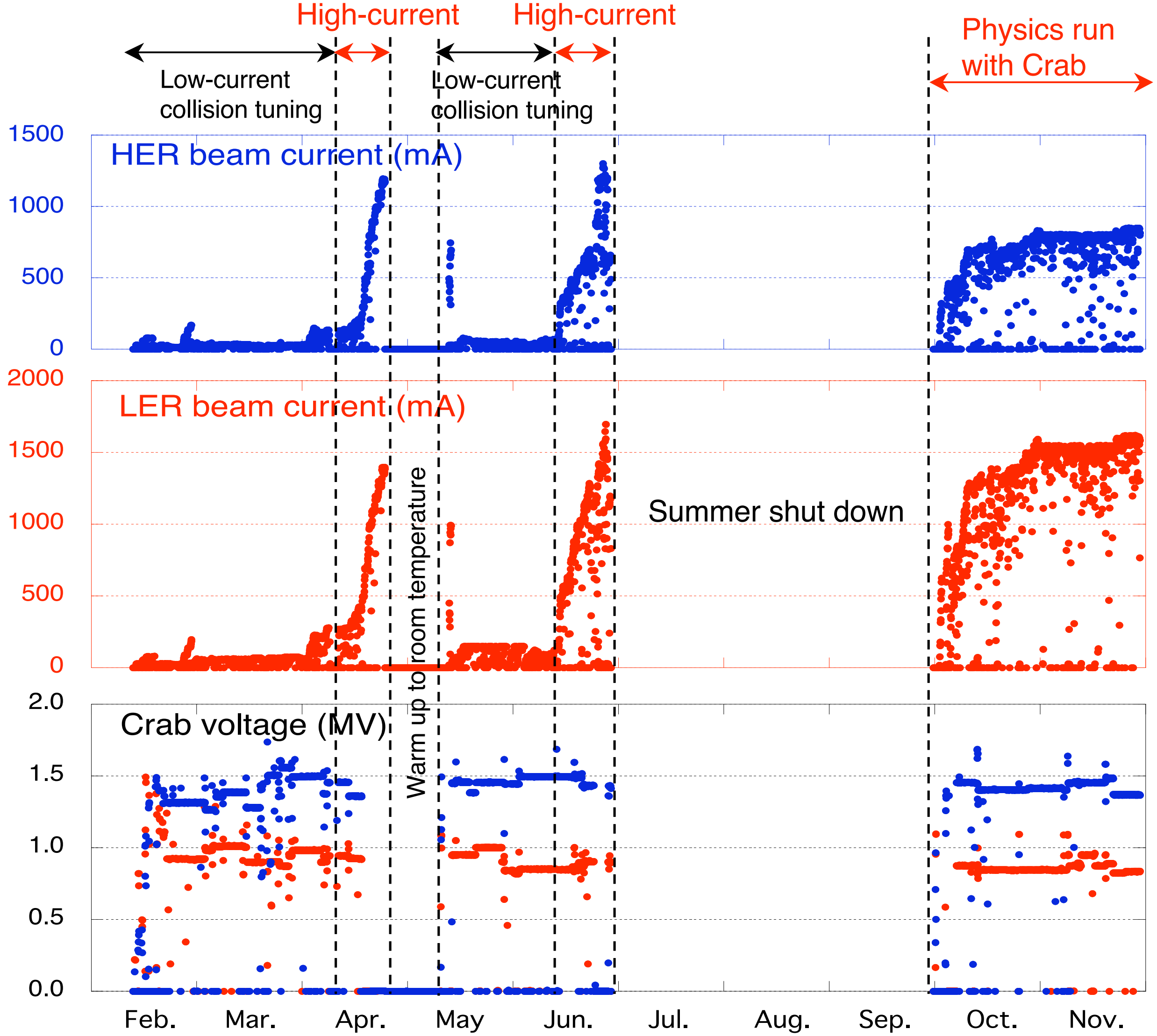
(K. Akai et al., Proc. B-factories, SLAC-400 p.181 (1992).)

Crab cavities in the KEKB tunnel

LER

HER

Overview of crab cavity operation



Achieved parameters during beam operation

	LER	HER	unit
Beam current (Crab ON)	1620	850	mA
Beam current (Crab detuned)	1700	1350	mA
Crab voltage (max)	1.6→1.3→1.1	1.7〜1.8	MV
Crab voltage (operation)	0.8〜0.95	1.3〜1.48	MV
HOM + LOM power	12	12	kW/cavity
Tuner phase stability (w/piezo) (w/o piezo)	± 13 ± 15	± 1 ± 3	degree degree
Crab phase stability	± 0.1	± 0.1	degree
Average trip rate (before summer) (since October)	1.6 0.4	1.3 3.5	times/day times/day

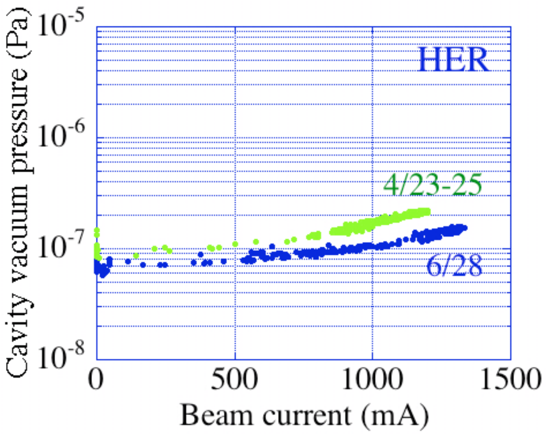
System Adjustment

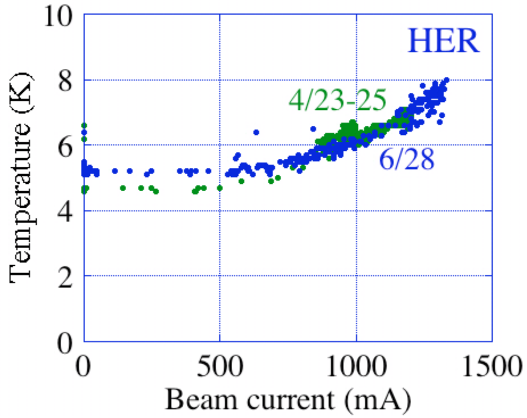
- Crabbing voltage
  - Calibrated from klystron output power and the loaded Q value.
  - The measurement to adjust the phase using beam (below) also gives an independent calibration of the voltage.
  - Both are in good agreement within a few percent.
- Crabbing phase
  - The reference phase is searched to minimize the beam orbit difference between the crabbing on and off, so that the bunch center is not kicked by the crabbing voltage.
  - In the high-current operation, the phase is shifted by 10 degrees from the reference phase to cure the oscillation observed at high-current crab collision (will be discussed later).
- Field center in the cavity
  - Searched by measuring the amplitude of the crabbing mode excited by a beam when the cavity was detuned. A local bump orbit was set to adjust the beam orbit on the cavity axis.

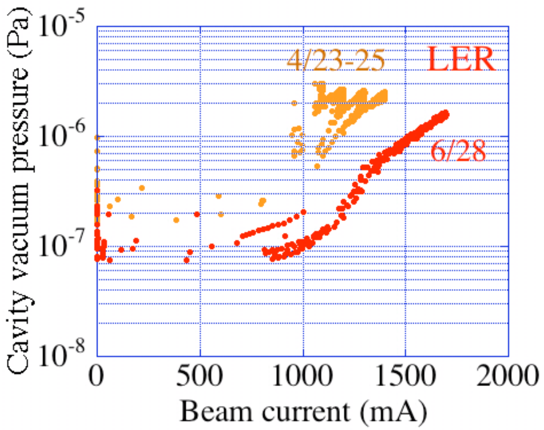
High beam current operation before summer

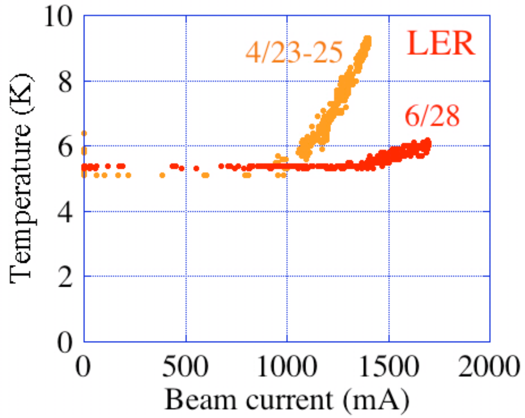
- Beam current increase
  - The number of bunches are increased, keeping the bunch current constant.
- First trial in April
  - Not very successful:
    - Vacuum pressure degraded, and the trip rate increased to an unacceptable level.
    - Another problem was temperature rise of the inner conductor of the coaxial beam pipe.
  - We suspended the trial,
    - detuned the cavities to scrub the beam pipe chambers using a high-current beam, and then warmed up to room temperature to remove the condensed gas on the surface.
- Second trial in July
  - Successfully performed.
    - We stored 1.7 A (LER) and 1.35 A (HER) with Crab detuned.
    - We stored 1.35 A (LER) and 0.7 A (HER) with Crab ON at that time.
  - The beam current was not limited by the cavity performance.

High current: improvements in June







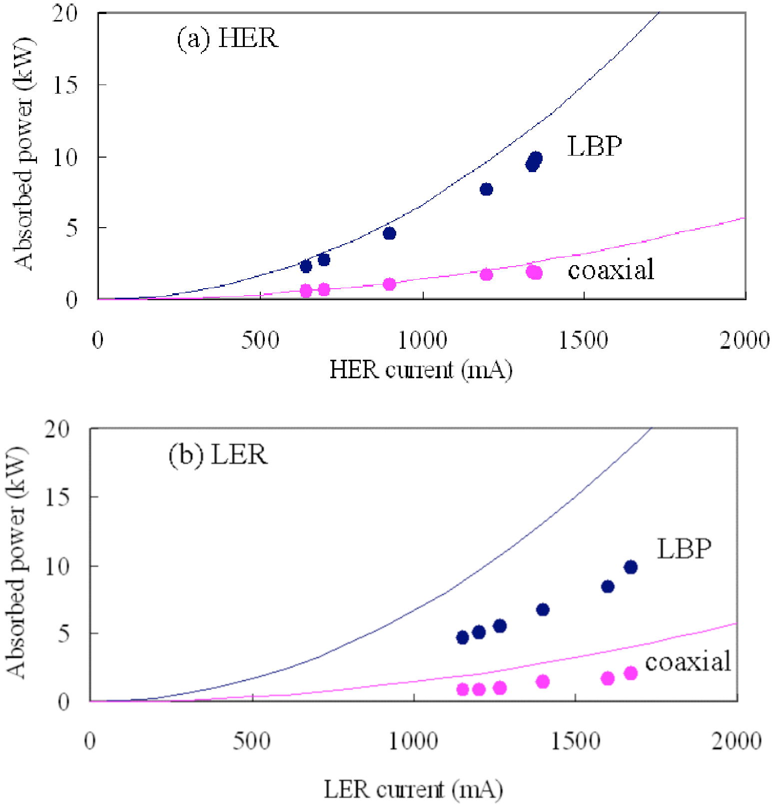


Vacuum pressure in the cavity before and after the warm up.

Temperature at the inner conductor of the coax before and after the reinforcement of the cooling power of the LER cavity.

High current: HOM power

Y. Morita

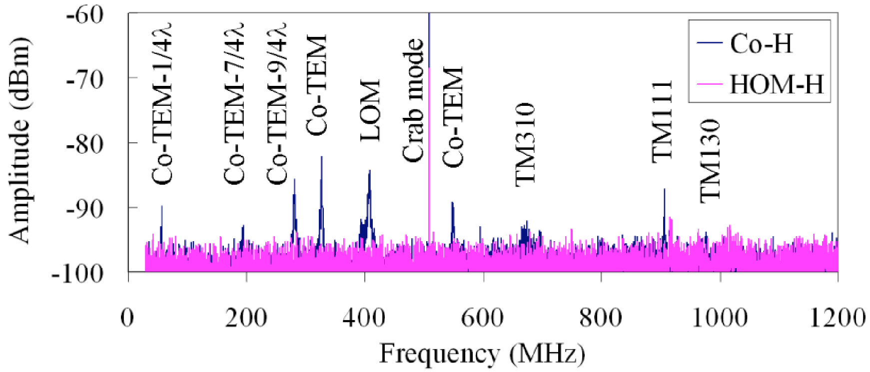


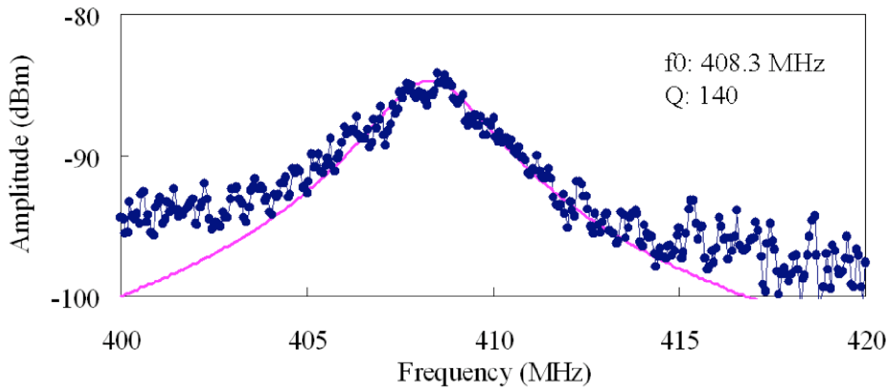
HOM power absorbed by the ferrite dampers at the large beam pipe (LBP) and the coaxial beam pipe. The lines are calculated value from the loss factor for σz = 6 mm.

- In each cavity, the HOM power absorbed by the ferrite dampers reached to 10 kW (LBP damper) and 2 kW (coax damper).
- Comparison with calculation:
  - The power absorbed by the HER dampers fairly agrees with the calculation.
  - In LER, a SiC damper is located at the downstream of the LBP ferrite damper, which absorbs 11 kW. The sum of the power absorbed by the SiC and ferrite dampers agrees with the calculation.
- The operation of the HOM dampers has been satisfactory and trouble-free.

Parasitic modes (HOM+LOM) spectrum

Y. Morita





- Spectrum observation
  - Beam-induced RF modes were observed during a machine study with a single bunch.
  - Signals from HOM-H port (LBP) mainly observes the beam spectrum, while signals from Co-H (coax) observes beam-induced RF modes around the coax.
- The Q-factor
  - Q of these modes were evaluated from the width. In particular, the most dangerous lower-order mode (LOM) is sufficiently damped to 140, consistent with calculation and a bench measurement.

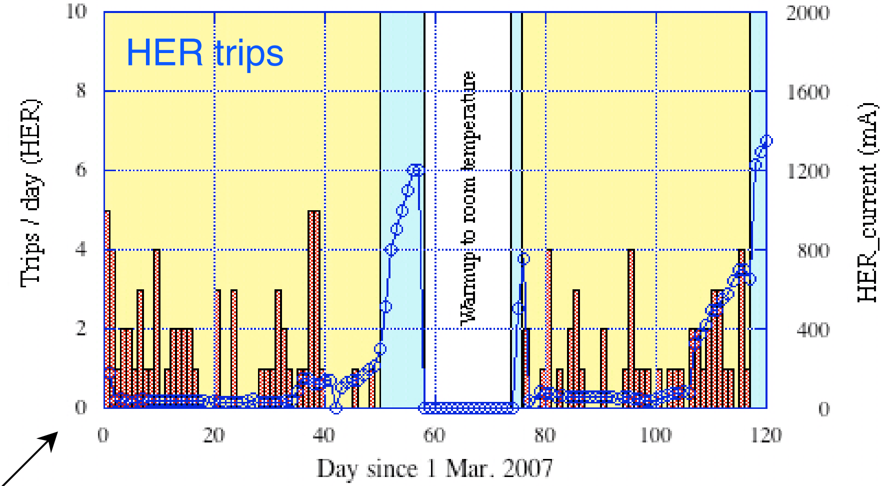
Crabbing voltage

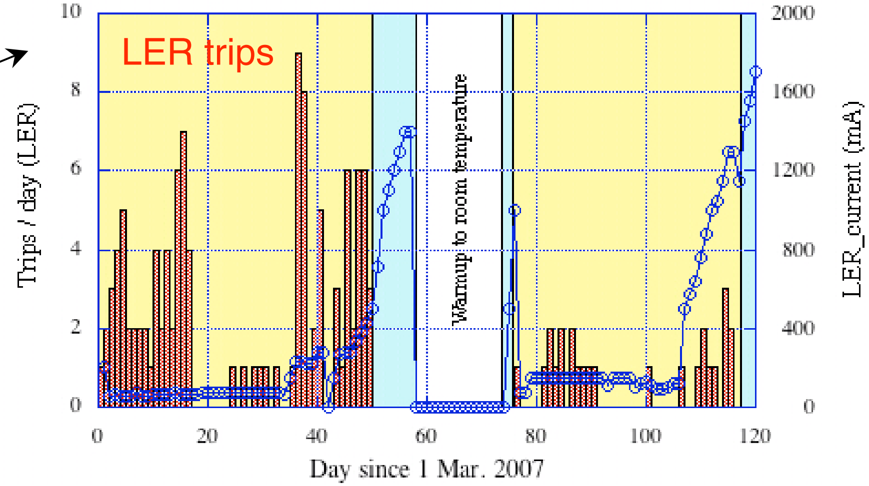
- HER crab cavity
  - The HER cavity has maintained high crabbing voltage: for most of the time it was operating at the design voltage of 1.45 MV.
  - The voltage was sometimes raised up to 1.7 MV to search for the best crabbing angle.
- LER crab cavity
  - The LER cavity degraded from 1.6 MV to 1.3 MV shortly after the installation in the tunnel.
  - After a heavy quench occurred on March 17, the LER cavity performance further degraded from 1.3 MV to 1.0 MV.
  - After warm up to 80 K, it slightly recovered to 1.1 MV. However, no further improvement has been achieved, even after the two times warm up to room temperature in April and in the summer shut down.
  - Fortunately, the necessary crab kick could be maintained by increasing the β_x @crab from 40 to 80 m.

Trips before summer

Table 3: Number of beam aborts due to the crab cavity trips and the average trip frequency.

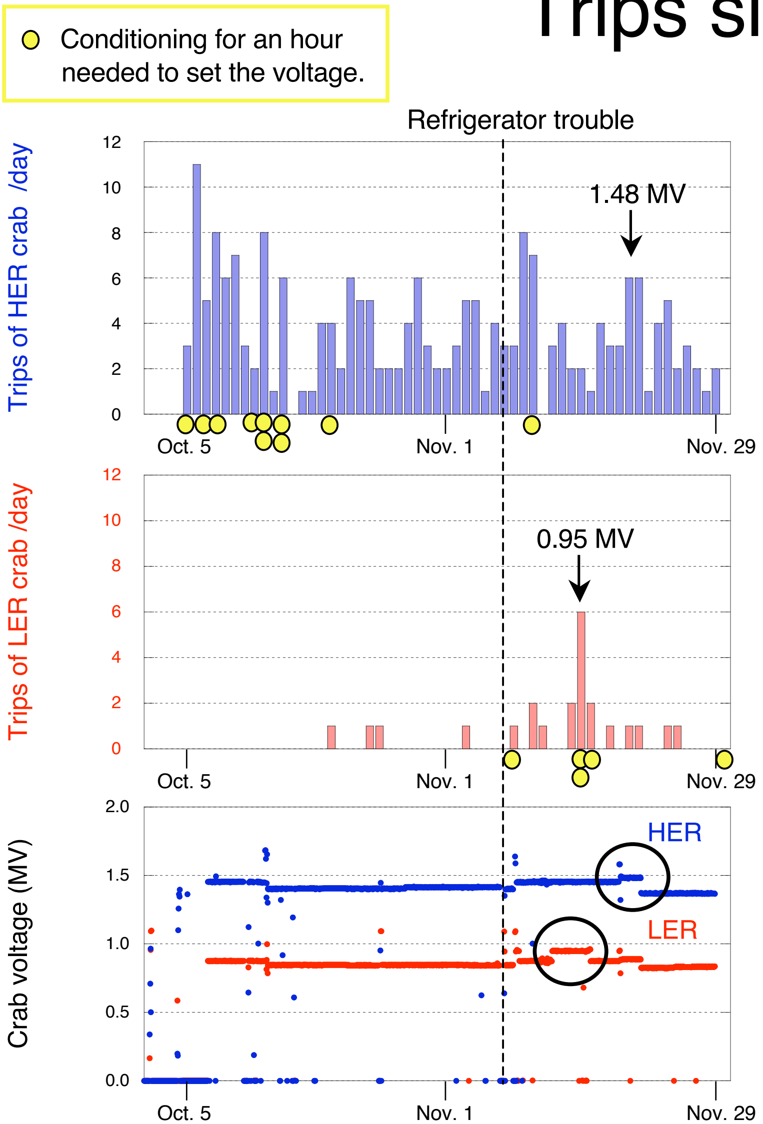
	Days for crabbing on	Number of trips	
		LER	HER
Mar. 2007	30	58	43
Apr.	17	54	21
May	16	13	16
Jun.	25	12	32
Total	88	137	112
Trips/day	—	1.56	1.27





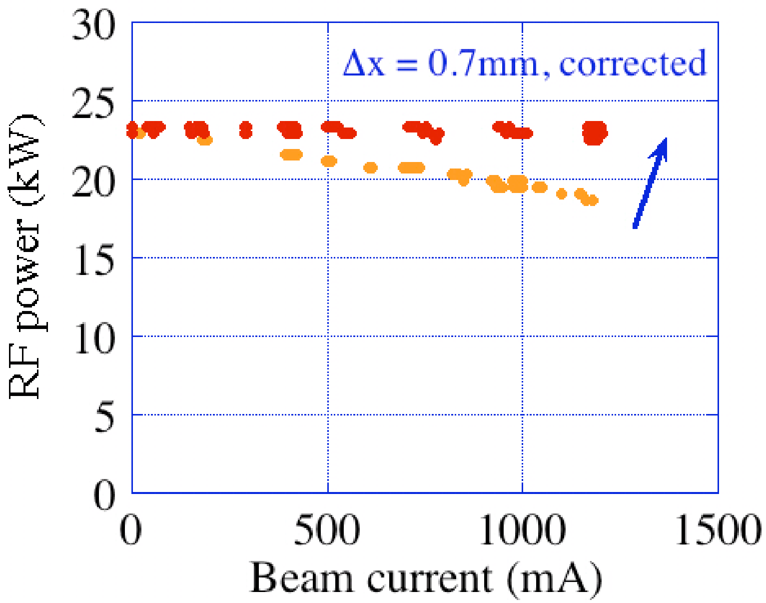
Number of crab cavity trips per day for four-month operation. They were operated in the period marked by the yellow area, whereas they were detuned in the period marked by the blue area. Blue circles show the maximum beam current in a day.

Trips since October



- Trip rate
  - The HER cavity had frequent trips at the beginning of October. Roughly, the trip rate has gradually decreased.
  - The average trip rate of HER cavity in the last 20 days is 2.7 times/day. The average trip rate of LER cavity in two months is 0.4 times/day.
- Voltage dependence
  - The LER trip rate was high when the voltage was raised from 0.875 MV to 0.95 MV for three days. Conditioning needed three times.
  - The HER trip rate seemed higher when the voltage was raised from 1.45 to 1.48 MV.
- The effect of accidental warm up of coax
  - The coax part was warmed up to 80 K due to refrigerator trouble (Nov. 7). The HER cavity had a higher trip rate after this event. The LER cavity needed conditioning after a trip.
  - The temperature of the coax was raised in the maintenance conditioning. The next day LER cavity needed conditioning due to MP at a low voltage (Nov. 30).

Beam-loading correction



- In the high-current operation, the beam-loading effect caused by a horizontal displacement of the beam orbit at the crab cavity was observed.
  - The RF power into the LER cavity decreased with an increase in the beam current.
- This situation was corrected with a local bump orbit.
  - LER orbit was corrected by 0.7 mm in June. Similarly, the HER beam orbit was corrected by 0.8 mm in Oct. 15.
- Once the local bump orbit is set, the orbit is stably kept by a local orbit feedback system.

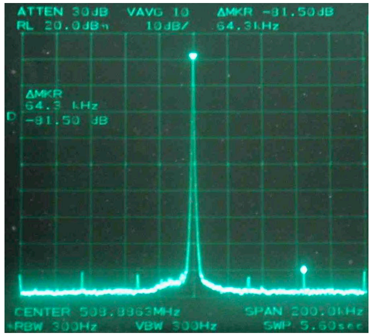
Relations between feedbacks for beam

- Vertex feedback
  - Data from the Belle detector is used to detect the longitudinal shift of the collision point. It is corrected by changing the LER RF phase (every 3 minutes).
  - Whether the LER crab phase needs to follow this change or not depends on the cause of the collision point shift. Anyway, in our system the LER crab does not follow this change.
- Horizontal feedback at IP (iBump-H)
  - Beam-beam kick is detected, and the relative horizontal displacement at the IP is corrected (～1 sec).
- Continuous Closed Orbit Correction
  - The orbit in the whole ring is corrected by the CCC system (10～20 sec).
- Local orbit feedback at crab
  - The orbit in the crab cavity region is monitored and corrected (2～3 sec). It has not been used since October.
- Crab phase
  - Controlled with respect to the reference RF at Nikko by the low-level RF feedback .
- Possible single kick generated by the relative phase shift between the crab and the accelerating RF is corrected by iBump-H and CCC.

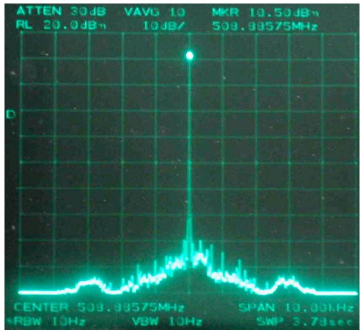
Phase stability

- 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.

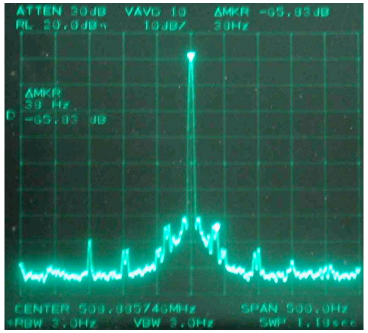
According to b-b simulation by Ohmi-san, allowed phase error for N-turn correlation is $0.1 \times \sqrt{N}$ (degree).



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

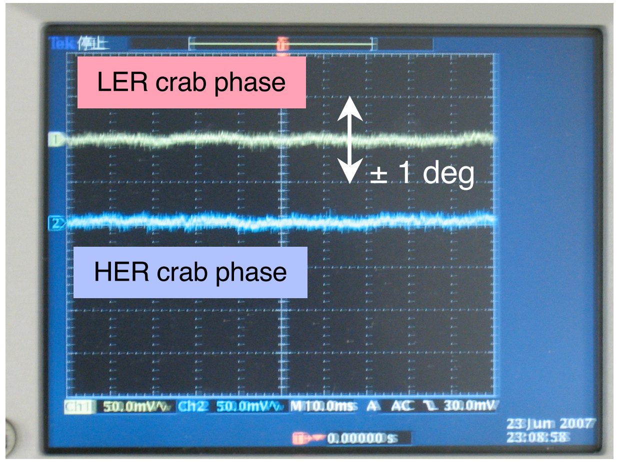


Span 10 kHz



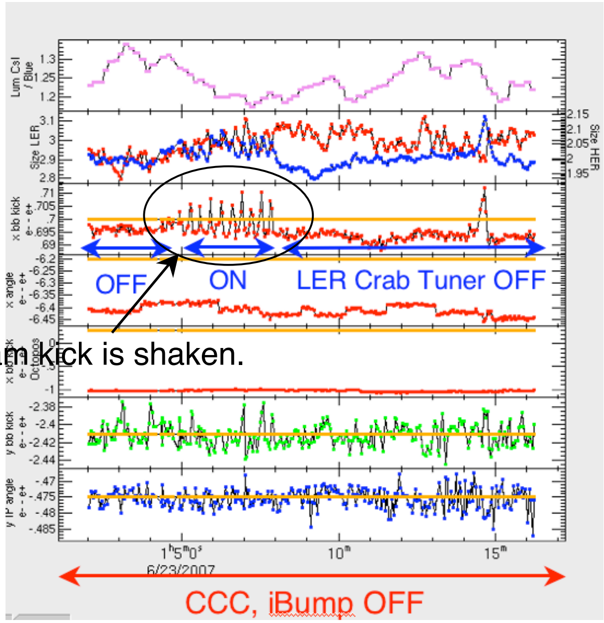
Span 500 Hz
Sideband peaks at 32, 37, 46, 50, 100 Hz.

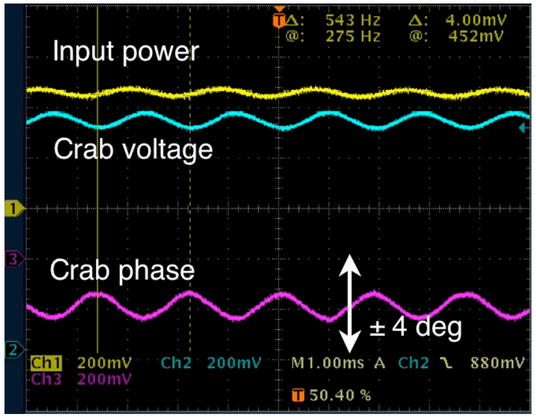
Spectrum around the crabbing mode measured at a pick up port of the LER crab cavity. Beam current was between 450 and 600 mA.



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

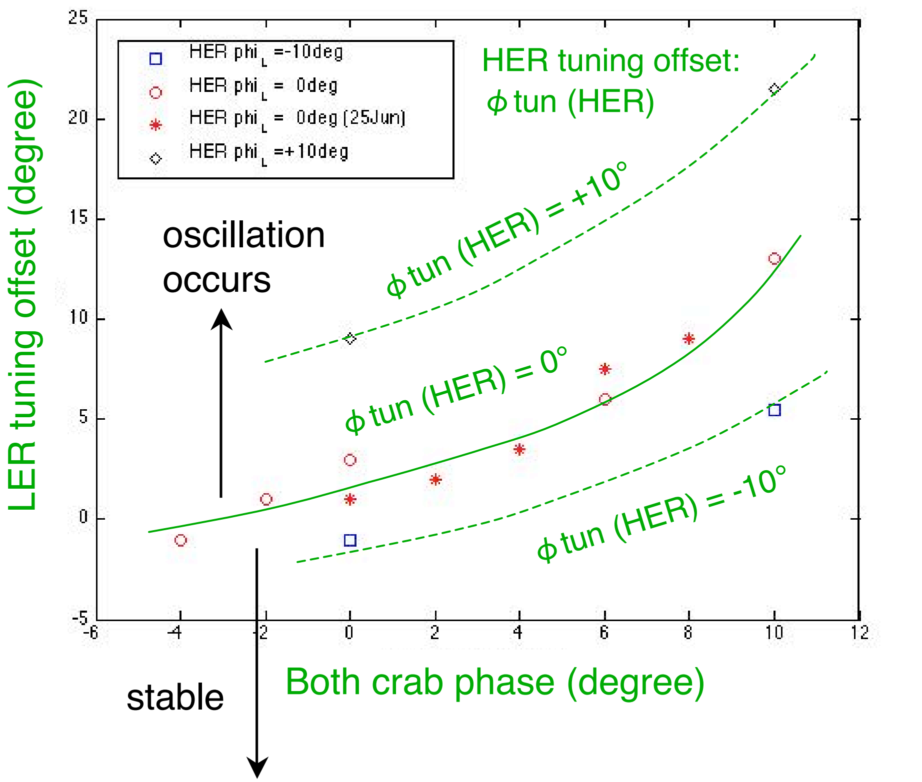
Oscillation of high-current crabbing beams





- A large-amplitude oscillation was observed in high-current crab-crossing operation in June.
  - It caused unstable collision, short beam life time and luminosity degradation.
  - Crab amplitude and phase were modulated at 540 Hz. Horizontal oscillation of beams was also observed at the same frequency.
  - None of the beam orbit feedback systems is responsible, since their time constants are 1 to 20 sec, much slower than the oscillation.
  - The oscillation occurred when the LER tuning phase migrated to the positive side. This gave us a hint to understand the phenomena.

A remedy for the oscillation was found



Dependence on the crab phase and tuning phase.
Beam current was 1150 mA (LER) and 620 mA (HER).

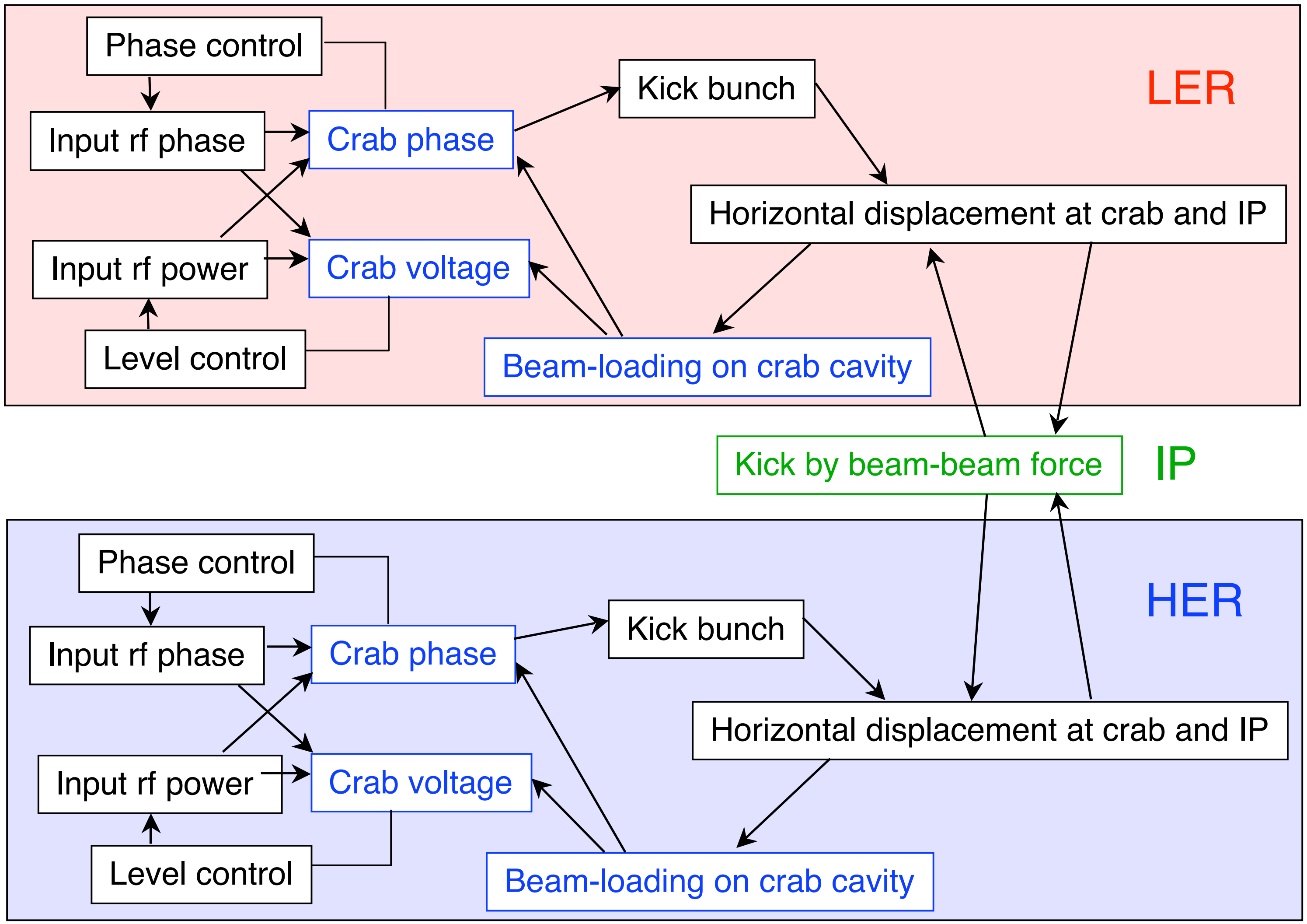
Observations at a machine study

- The oscillation occurred only with high-current colliding beams: it never occurred with a single beam, even at a high current.
- Both beams oscillates coherently.
- The threshold for the oscillation is dependent on the crab phase and tuning phase (see left).

Cause and remedy

- We concluded that the oscillation is caused by beam loading on crab cavities together with beam-beam force at the IP (see, next slide).
- We found that it can be avoided by shifting the crabbing phase by +10° and controlling the tuning offset angle appropriately.

Possible mechanism of the oscillation



Frequency tuner problems

- LER tuner fluctuation
  - LER tuner has a large backlash behavior due to a mechanical problem. As a result, the tuning phase fluctuates by about ± 15°.
- Piezo elements were broken many times.
  - LER piezo was broken twice in June.
  - HER piezo was broken three times in October.
  - Since then, the tuners of both cavities have been operating without the piezo. HER tuning phase fluctuation is increased from ± 1° to ± 3°.
- Is it OK without piezo?
  - The crabbing phase is stably controlled by the low-level feedback system, even when the tuning phase is largely fluctuated.
  - However, the large fluctuation of the tuning phase is unfavorable for the oscillation at the high beam current. (As described, the oscillation threshold is sensitive to not only the crab phase, but also the tuning phase.)

Hardware issues to be solved

- Recover the LER voltage.
  - Has not been recovered by warm up and/or any conditioning so far.
  - Re-treatment of the cavity before upgrading of KEKB?
- Improve the frequency tuner.
  - Large backlash of the LER tuner.
  - Using a piezo element is desired for further increase of the beam current.
- HER cavity has higher trip rate after the warm up. It takes several weeks to reduce the trip rate.
  - Because of a higher voltage than LER?

Summary_1

- High beam currents of 1.7 A (LER) and 1.35 A (HER) were successfully stored with the crab cavities.
- Beam instability caused by the crabbing mode, the LOM, or any HOM has not been a problem.
- HOM power reached 10 kW for the LBP and 2 kW for the coax. The dampers have not caused any problem.
- LER crab voltage has degraded to 1.1 MV. The necessary kick is maintained by increasing the βx @crab.
- Trip rate during the physics run is about 3 times/day for the HER cavity and 0.4 times/day for the LER cavity. Warm up was effective to reduce the trip rate of LER cavity.
- Although the tuning phase has a large fluctuation, the stability of the crabbing phase satisfies the requirement.
- The oscillation observed with the high-current crabbing beams was successfully avoided by shifting the crab phase by +10°.

Summary_2

- KEKB crab cavities have been really working with high beam currents to conduct physics run with the crab crossing !!!