RF system of crab cavities

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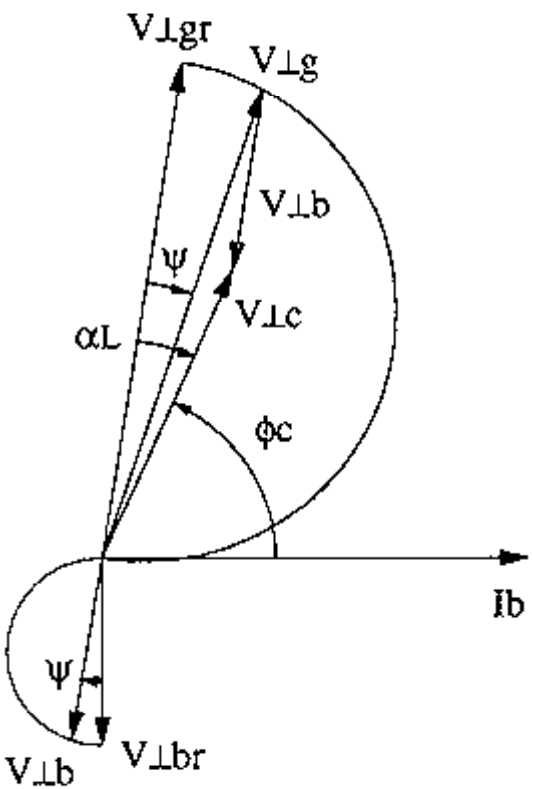
for the KEKB crab cavity group

Beam-loading and loaded-Q factor

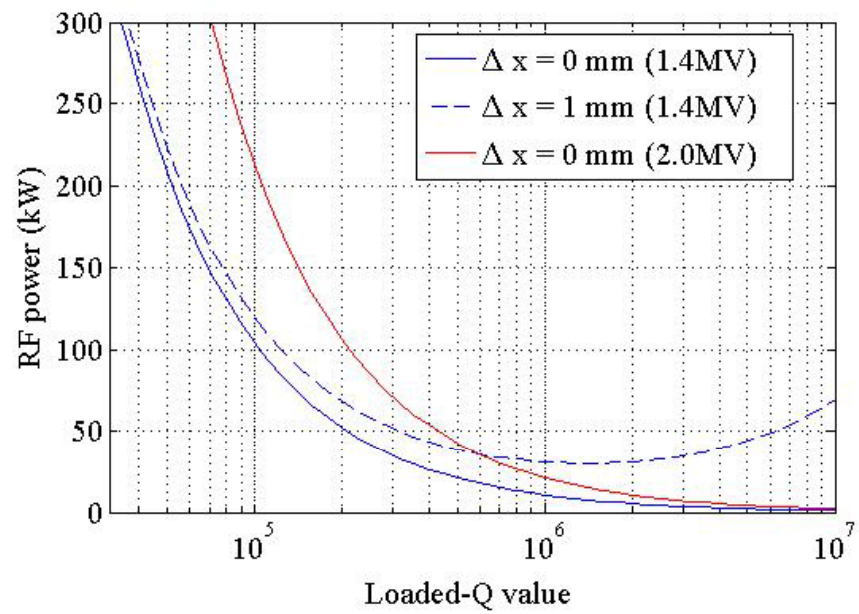
K. Akai et al, EPAC96, p. 2118.

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



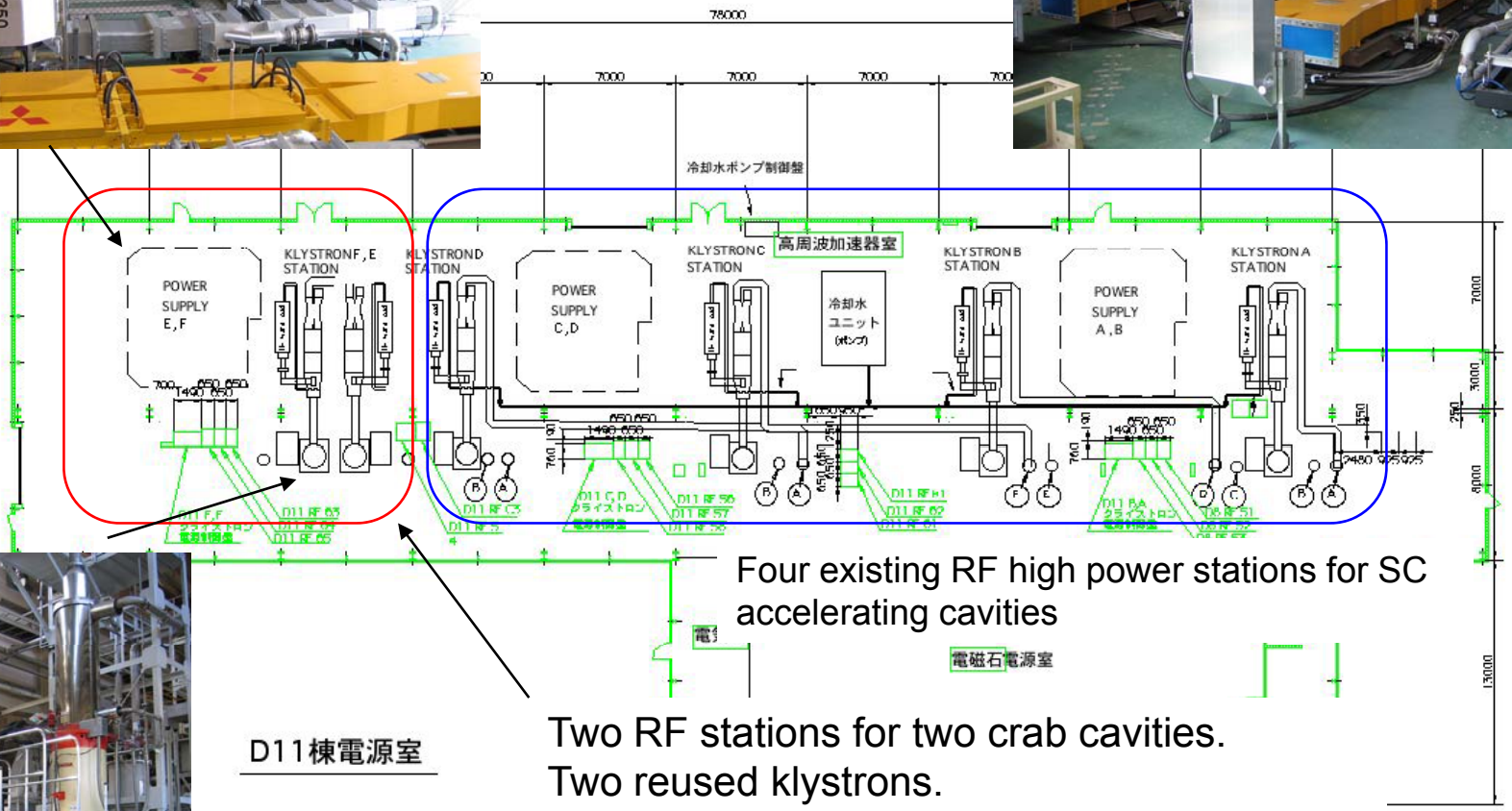
Vector relation for the crabbing mode

Required power to maintain the crabbing voltage.
Beam induced voltage (0.2MV for Ib=2 A, QL=2x105, dx=1 mm)



Not to be sensitive to beam orbit change.
Q_L=1-2 x 10^5 is a good choice.
Q_L=1.34x10^5 (HER)
Q_L=2.07x10^5 (LER)

High power RF system



Four existing RF high power stations for SC accelerating cavities

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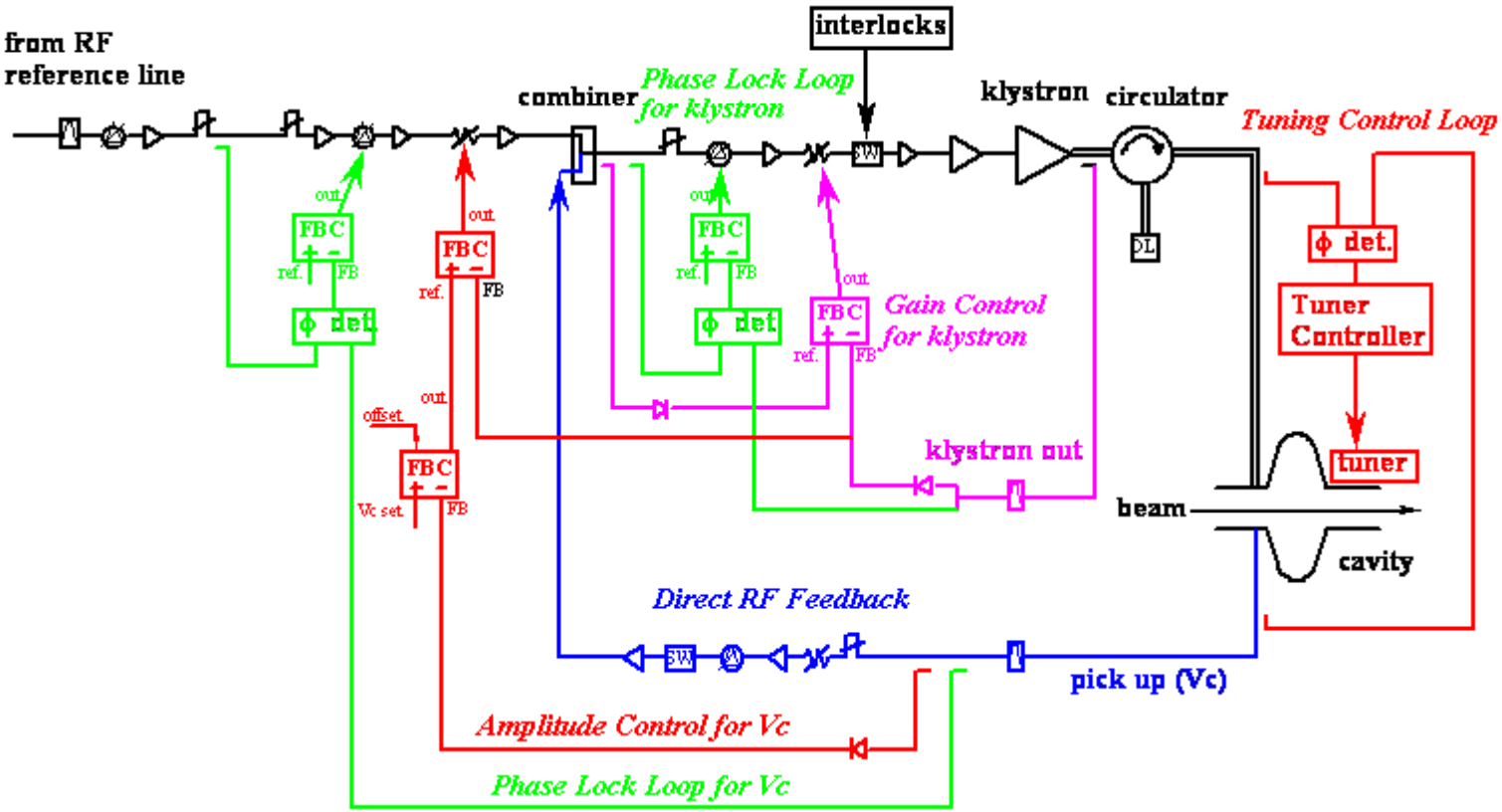
Two RF stations for two crab cavities.
Two reused klystrons.
One power supply to drive two klystrons.
Similar to the SC accelerating cavity stations.

Low level RF system

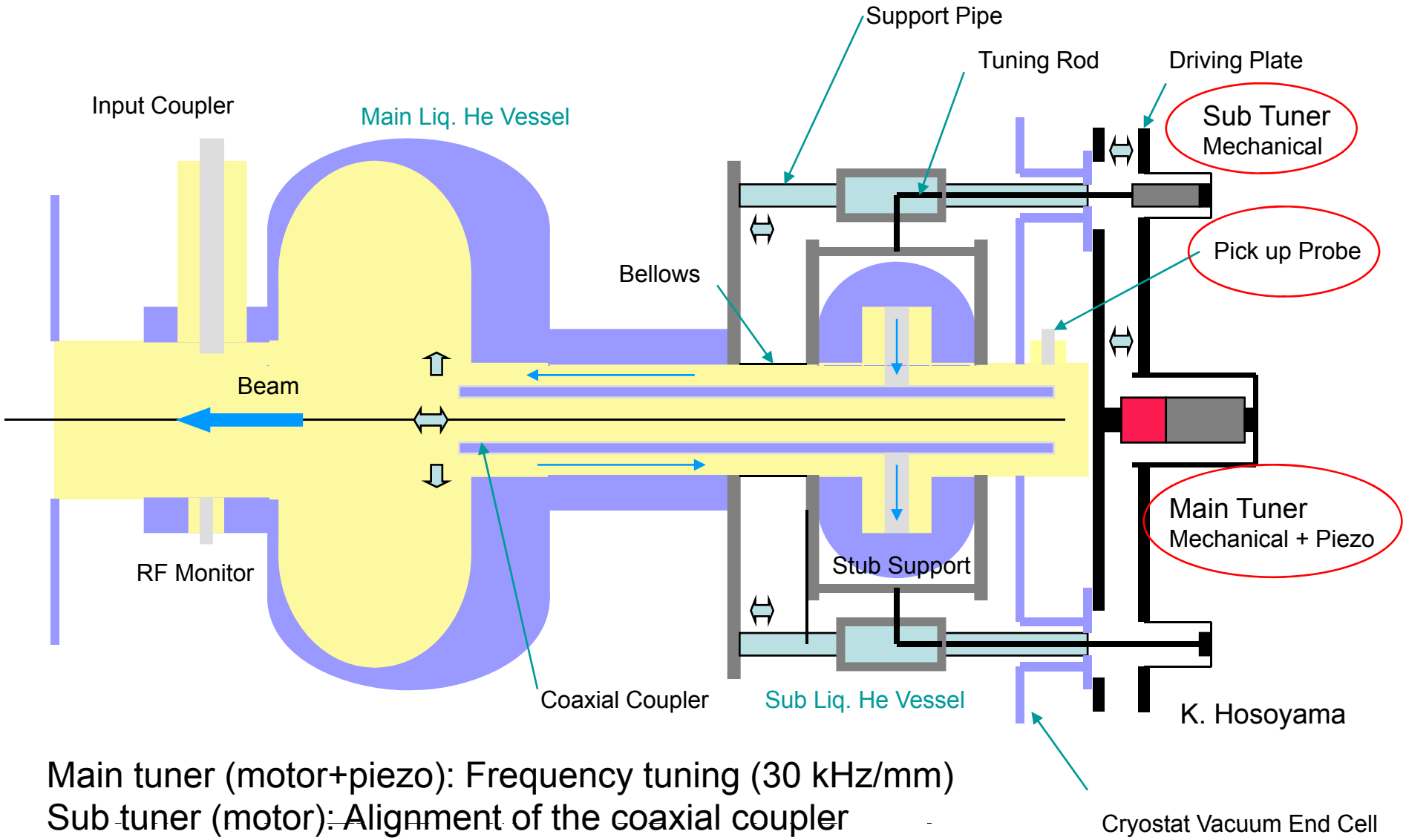
K. Akai et al, EPAC98, p. 1749.



Mostly similar to the low level system for the SC accelerating cavities.

Conventional amplitude and phase feedback loops to control the cavity voltage and the klystron output power.

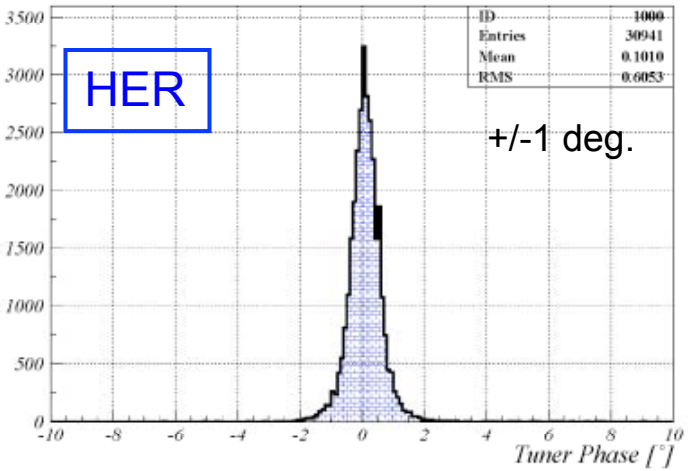
Frequency Tuning Mechanism

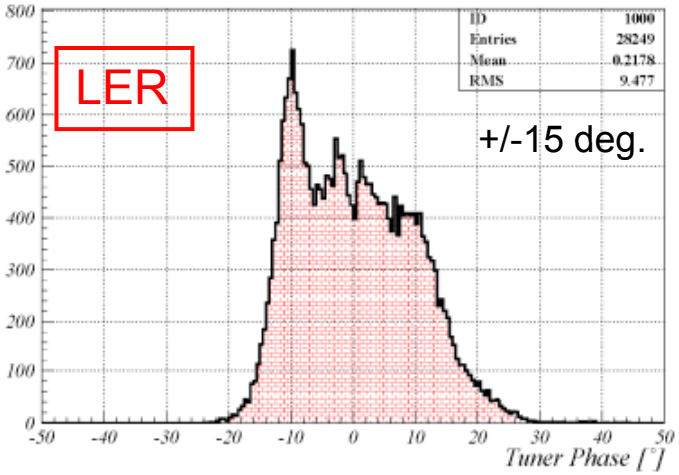


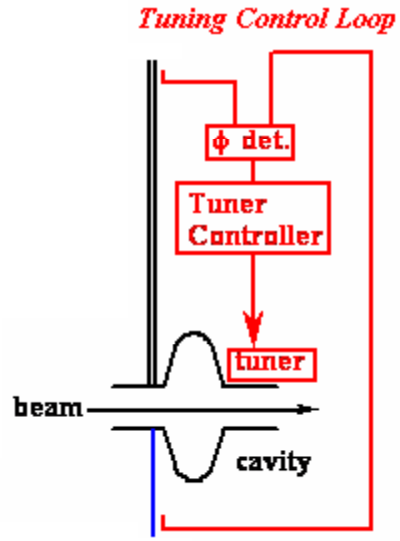
Main tuner (motor+piezo): Frequency tuning (30 kHz/mm)
Sub tuner (motor): Alignment of the coaxial coupler
Pick-up probe for monitoring crabbing-mode leakage

Tuner phase control

Distribution of tuner phase for Vc > 0.3 MV

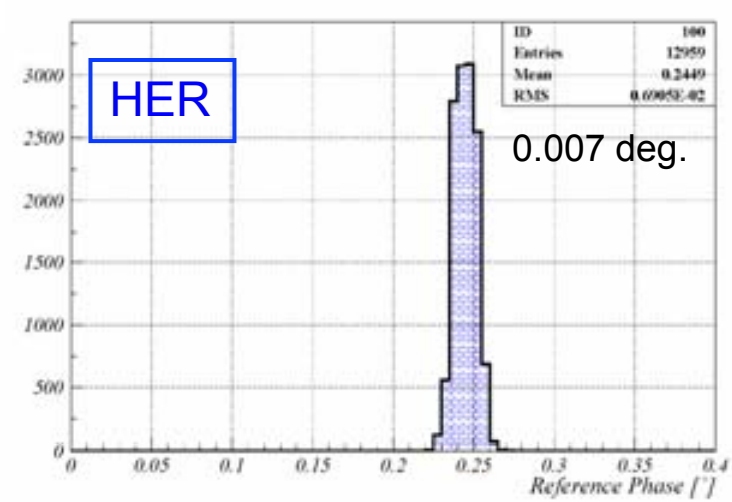


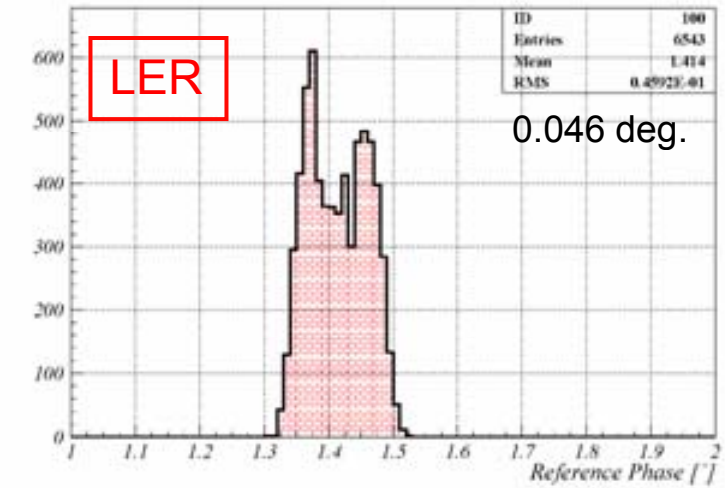


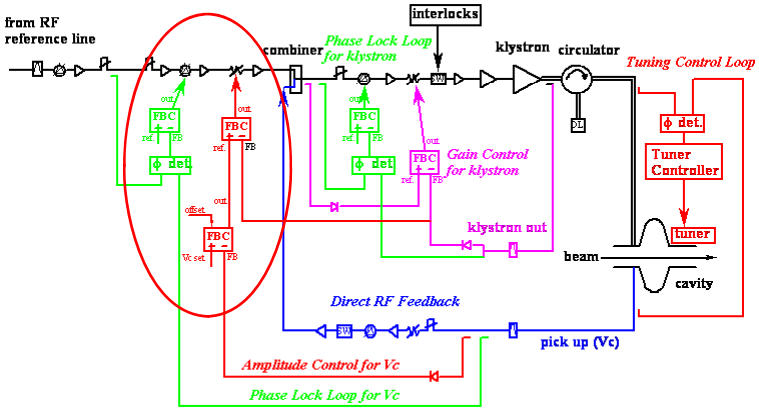


The HER frequency tuner is well controlled.
Tuning phase stays within +/- 1 deg.
The LER frequency tuner mechanism has a large backlash.
(Its cause is not identified yet)
Tuning phase fluctuates about +/- 15 deg.

Crab phase control







Low level feed back loops well stabilize the cavity voltage and phase.
Phase distributes within
0.007 deg. in the HER crab cavity,
0.046 deg. in the LER crab cavity.

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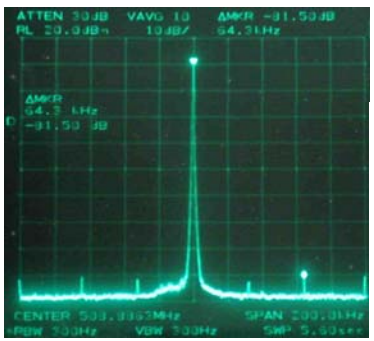
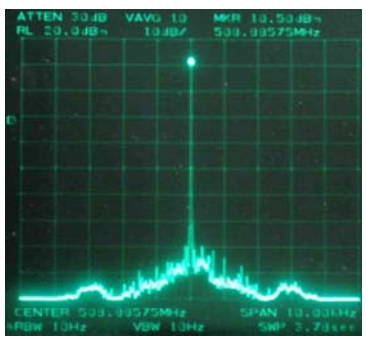
Phase stability

- 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.

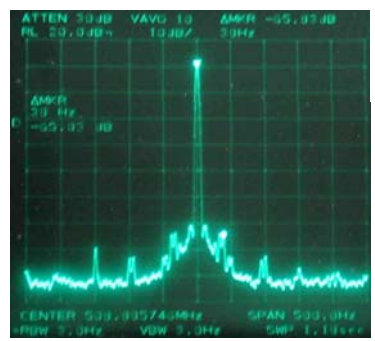
According to b-b simulation by Ohmi-san, allowed phase error for N-turn correlation is 0.1 × √N (degree).



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

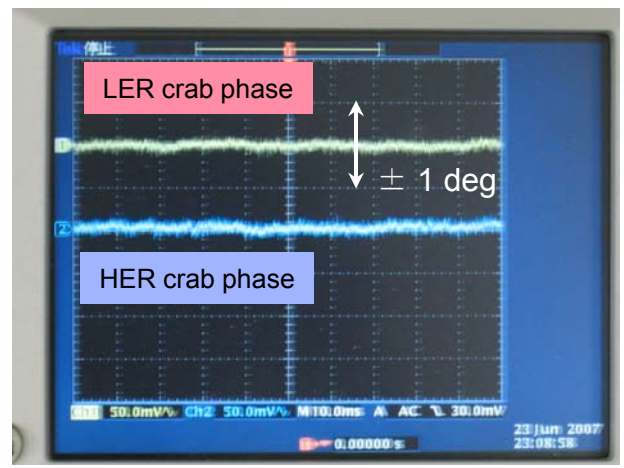


Span 10 kHz



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).

System adjustment

$$P_g = \frac{{V_c}^2}{4\left(\frac{R_\perp}{Q_0}\right) Q_L}$$

- Crabbing voltage
  - Klystron output power and unloaded Q factor give the crabbing voltage (Vc)
  - Beam orbit distortion measurement gives the Vc
  - Both agree well (within a few %)
- Crabbing phase
  - Reference phase was searched to minimize the beam orbit distortion.
- Field center in the cavity at low current (beam-induced power)
  - A local bump orbit was set with the crab cavity detuned
  - Minimum beam induced voltage
- Field center in the cavity at high current (beam loading)
  - Minimum beam loading

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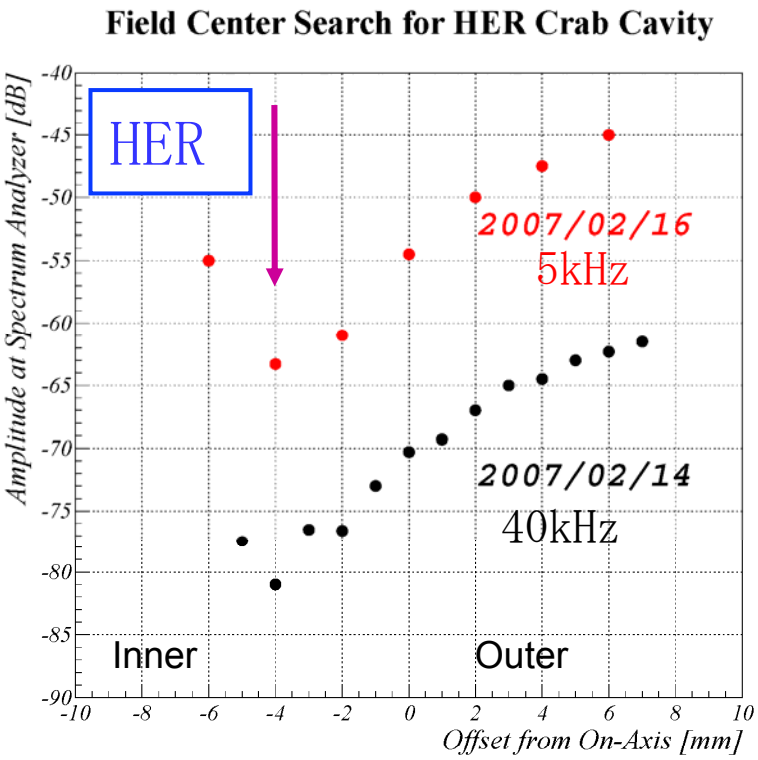
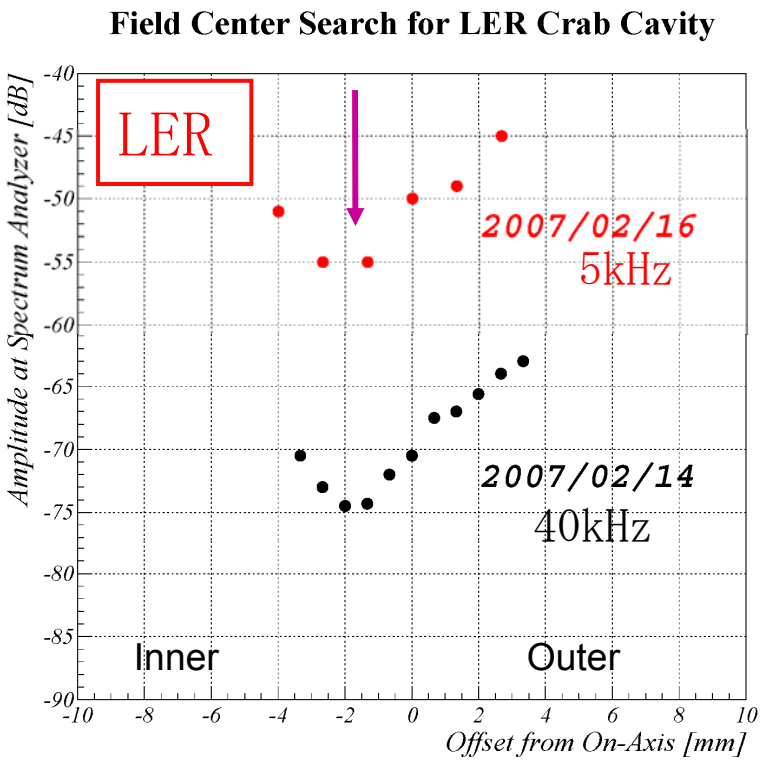
Searching Field Center in Crab Cavity





- Field center was searched by measuring the crabbing mode amplitude excited by a beam with the crab cavity detuned. Two measurements with different detuning frequencies agreed to each other.
- A local bump orbit was set to make the beam aligned on the field center.

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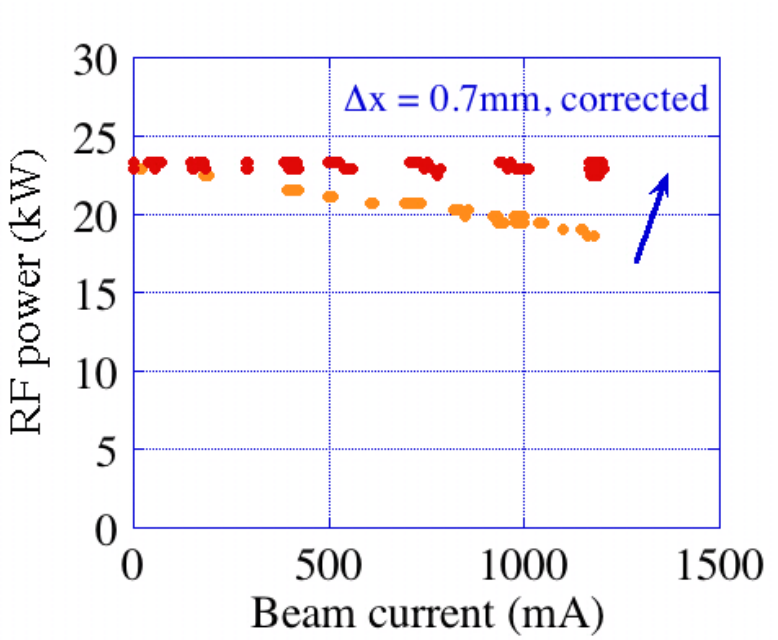
Beam-loading correction



- 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.

Overview of crab cavity operation

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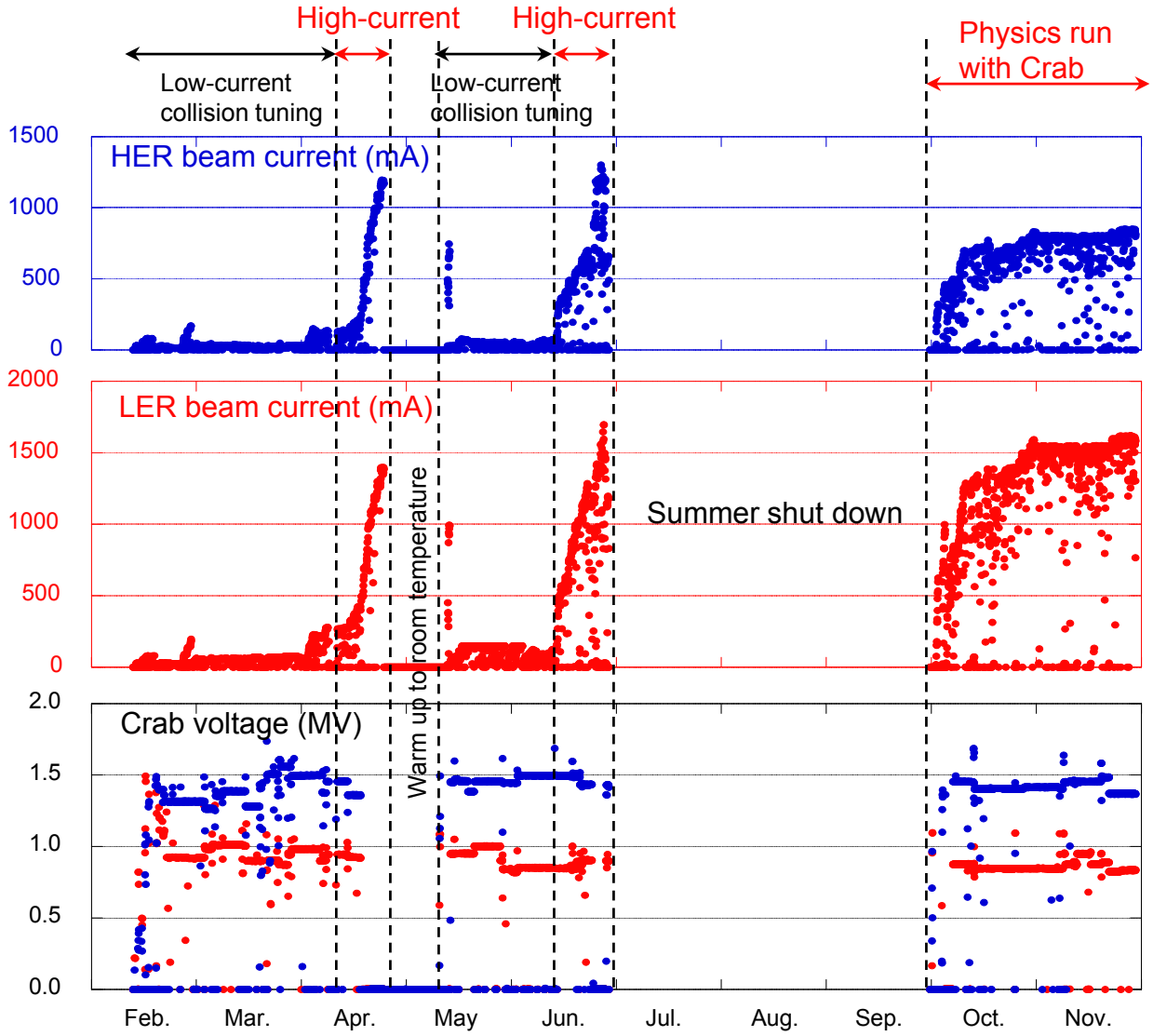

Trip rate 1.27/1.56

Trip rate 2.7/0.4

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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.

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Achieved parameters during beam operation

	LER	HER	unit
Beam current (Crab ON)	1620	850 (950)	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 (13)	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
(Feb. 12-23)	0	<1.0	

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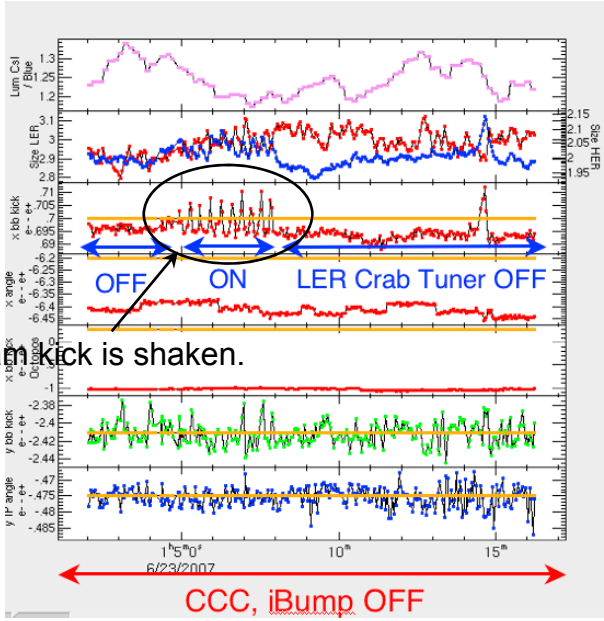
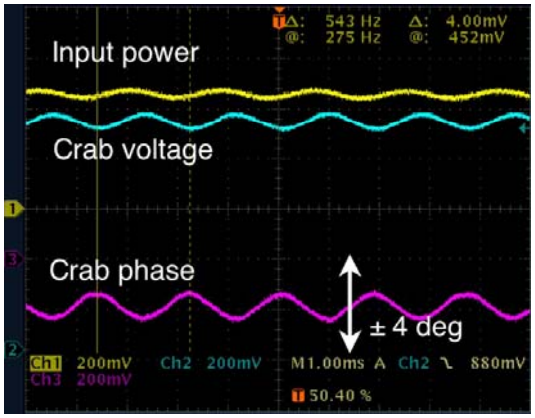
Oscillation of high-current crabbing beams





- 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.

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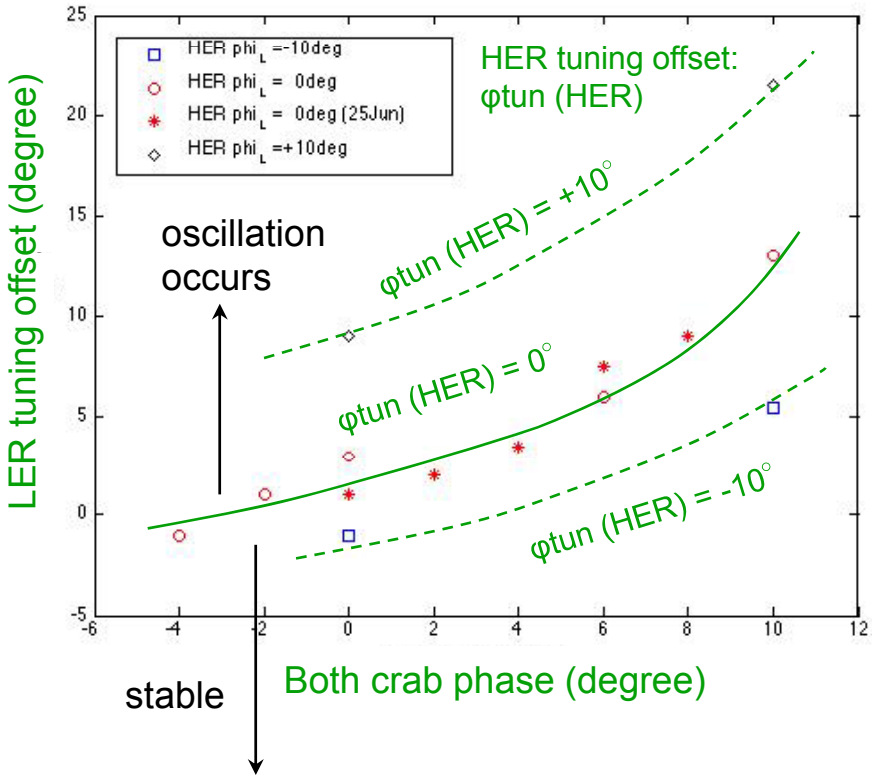
A remedy for the oscillation was found



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.

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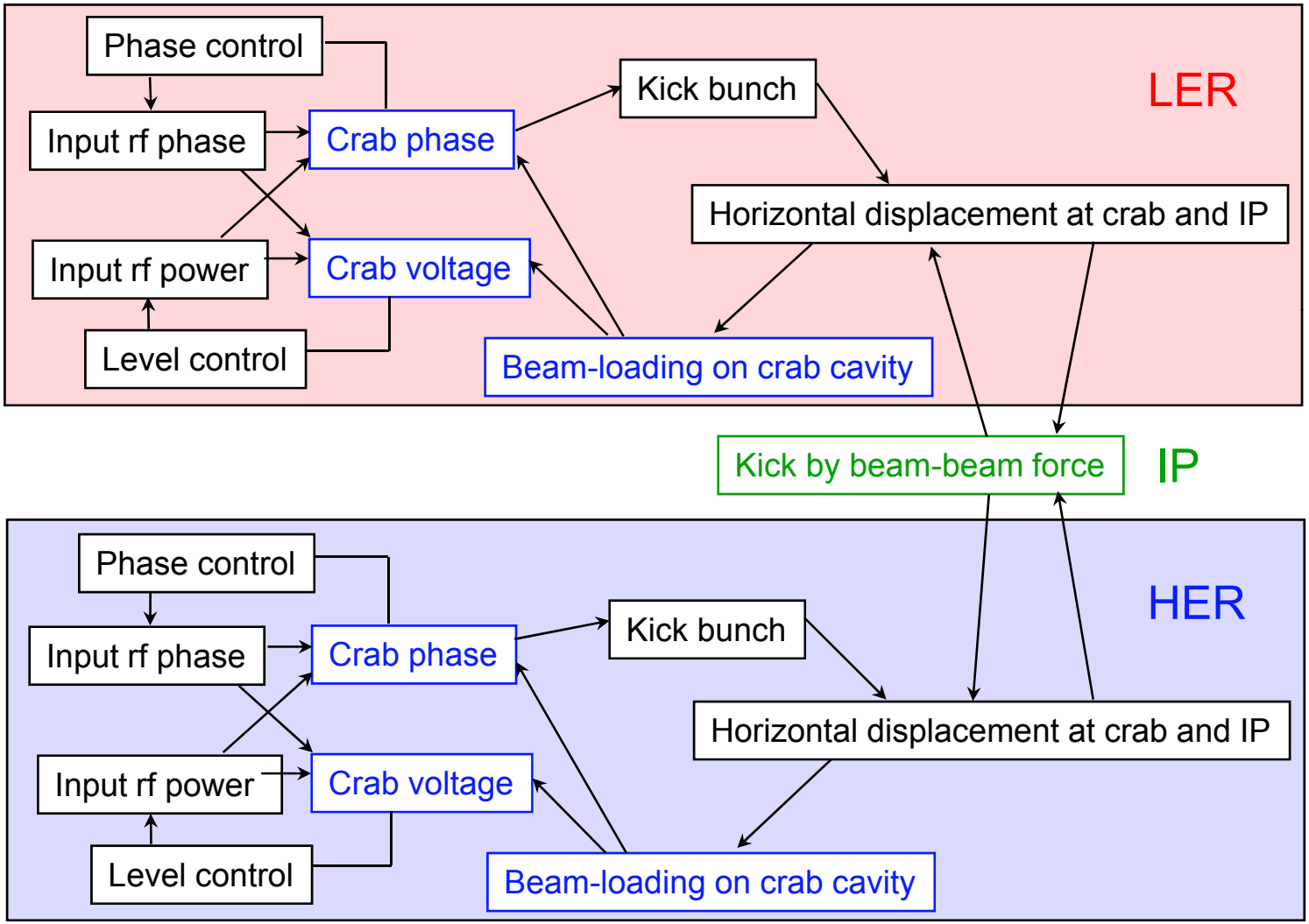
Possible mechanism of the oscillation



Summary

- High beam currents (1.7/1.35 A) stored with crab cavities.
- No serious beam instability caused by LOM/HOM.
- HOM power successfully absorbed up to 12 kW in the ferrite dampers.
- Physics run with CRAB ON with high beam currents (1.62/0.95 A).
- LER crab voltage degraded to 1.1 MV.
  - Still applicable by increasing beta-x at the LER crab cavity.
- Crab phase well controlled, although the LER tuner phase fluctuates.
- The beam oscillation observed with high current crabbing operation.
  - Can be avoided by shifting crab phase by +10 deg.
- Trip rate during the physics run 0.4/3.5 par day (last year).
  - Trip rate of the HER cavity is less than 1/dey this year.
- KEKB crab cavities have been working with high beam currents to conduct physics run with the crab crossing !!