KEKB experience with crab cavities

20230717

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KEK

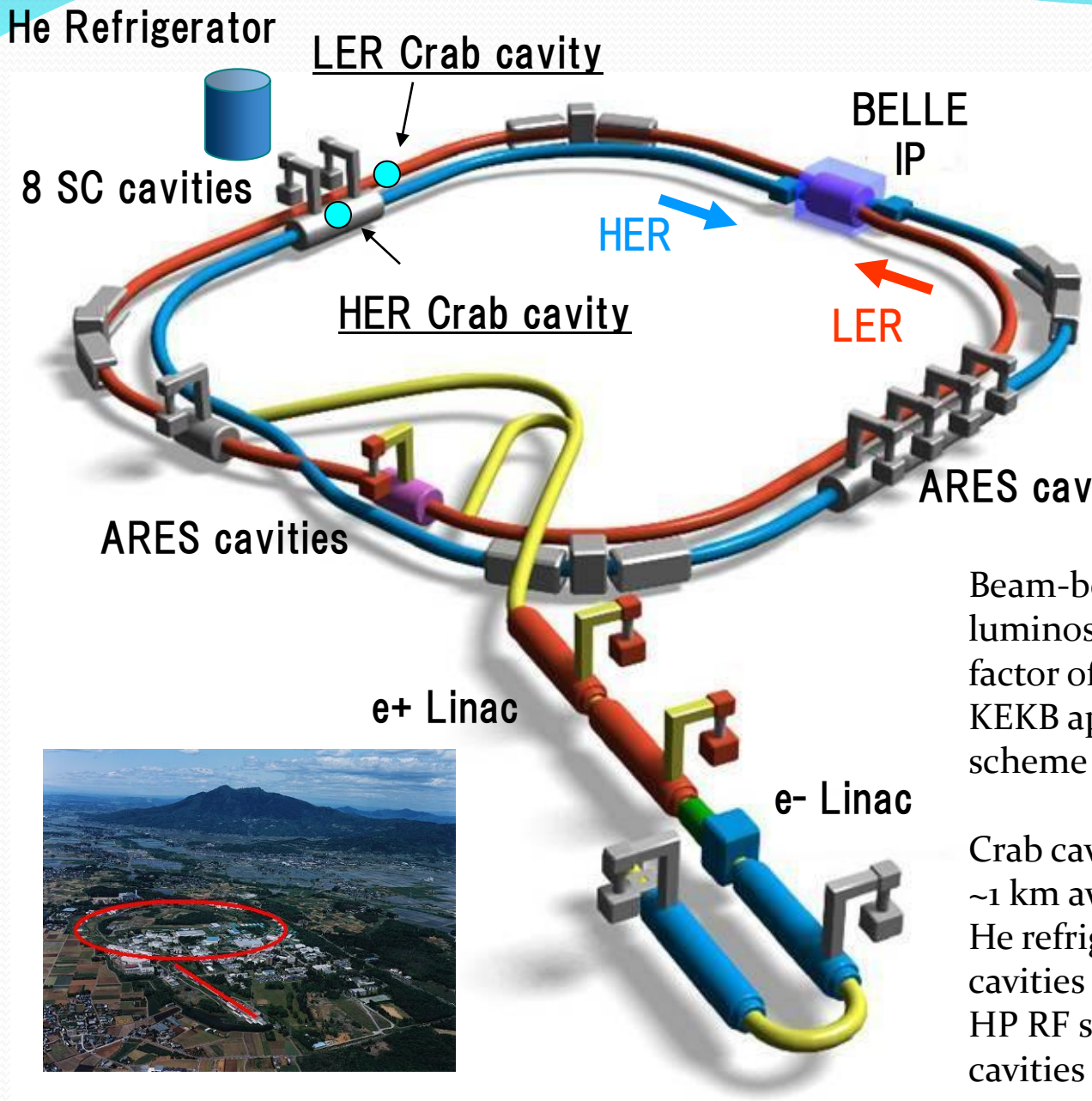
KEKB experience with crab cavities

- KEKB accelerator and crab crossing
- RF system
- Crab cavity commissioning
- Crab cavity operation

KEKB

Double ring e+e- collider

LER: e+ 3.5 GeV 1.7A
HER: e- 8.0 GeV 1.4A
Cross. Angle: 22 mrad



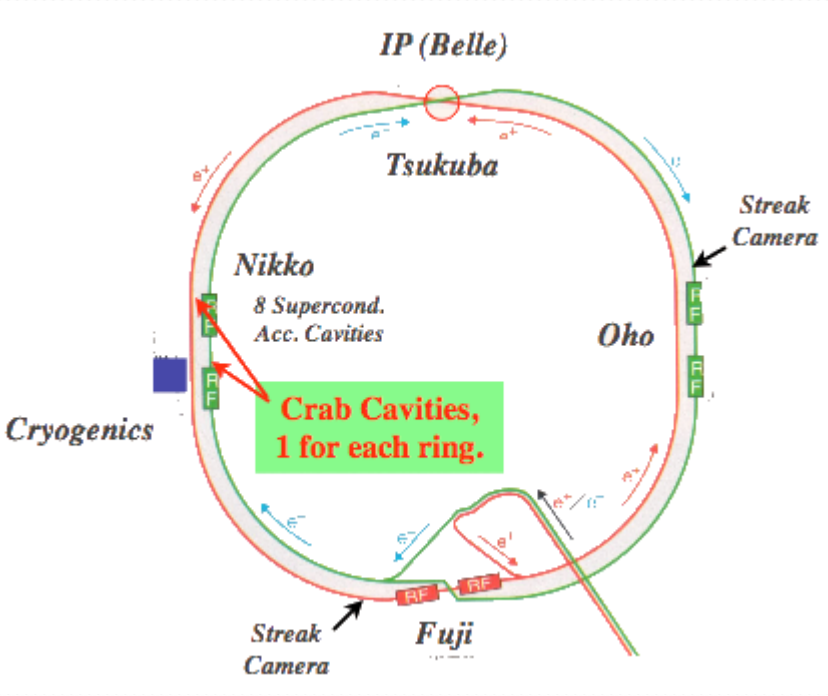
Beam-beam simulation predicted luminosity can be increased by a factor of 2 or more with crab crossing
KEKB applied the single crab cavity scheme

Crab cavity location
~1 km away from the IP
He refrigerator (8 kW@4.4K) for 8 SC cavities
HP RF stations re-used for crab cavities

Single crab cavity scheme

- Typical parameters

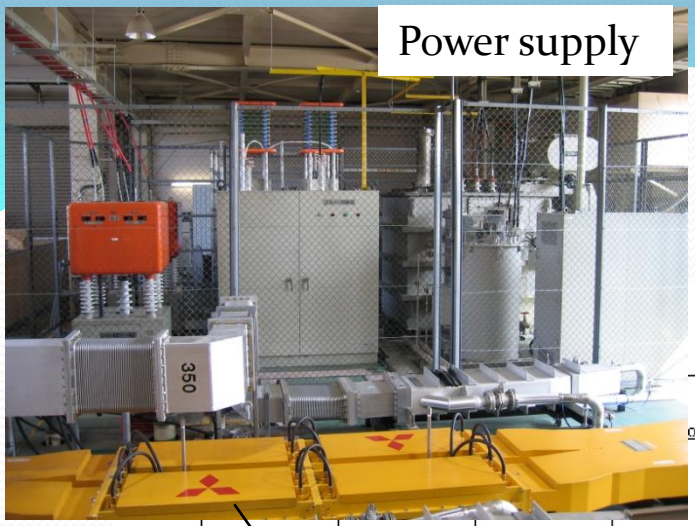
	LER	HER
Beam energy (GeV)	3.5	8.0
Beam current (A)	1.7	1.25
RF frequency (MHz)	508.887	
Crossing angle (mrad)	±11	
$\beta_{x,IP}$ (cm)	80	80
$\beta_{x,crab}$ (m)	80	170
Kick voltage (MV)	0.9	1.45
Loaded Q	2.0×10^5	1.6×10^5
RF power (kW)	23	90

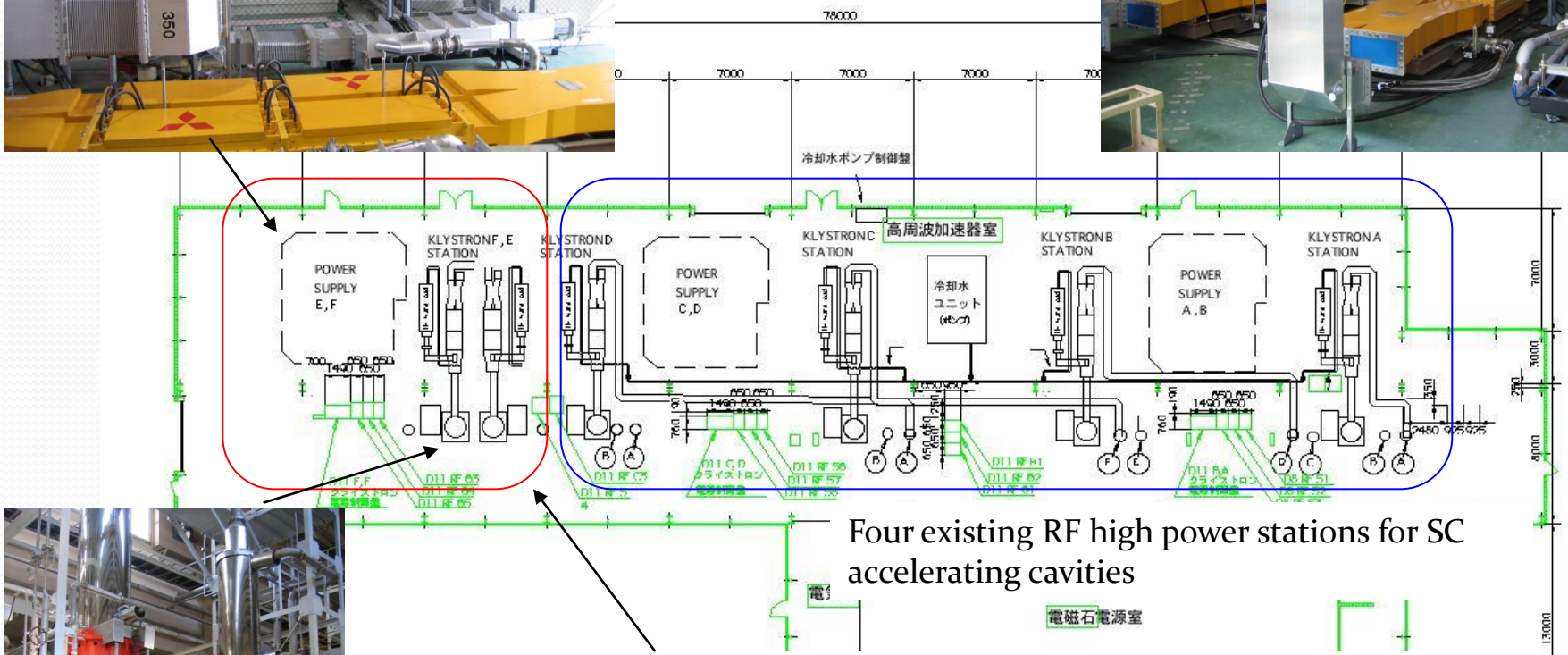


RF system

- High power station
- Low level control
- Interlock

High power RF system



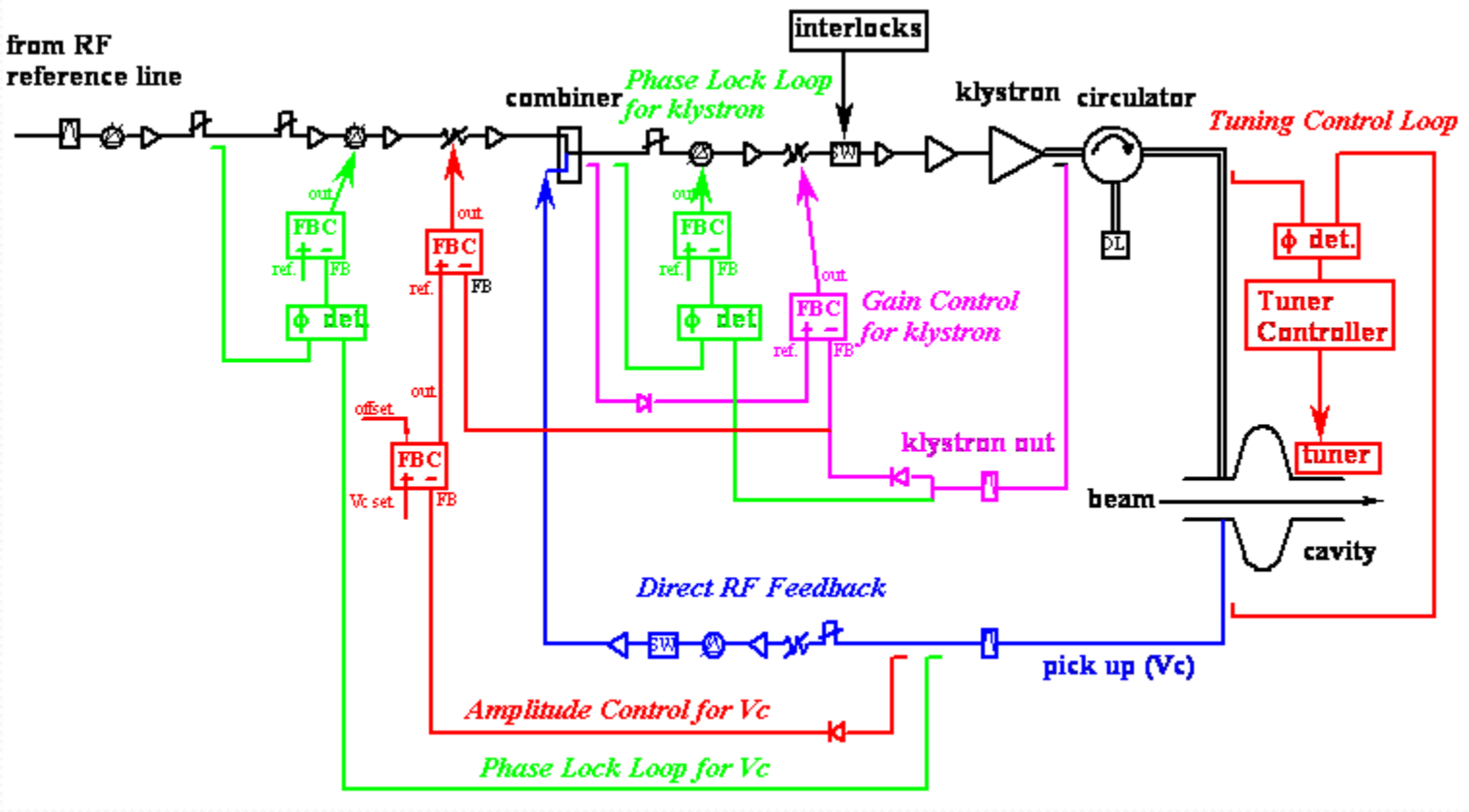


Four existing RF high power stations for SC accelerating cavities

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

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

Low level RF system

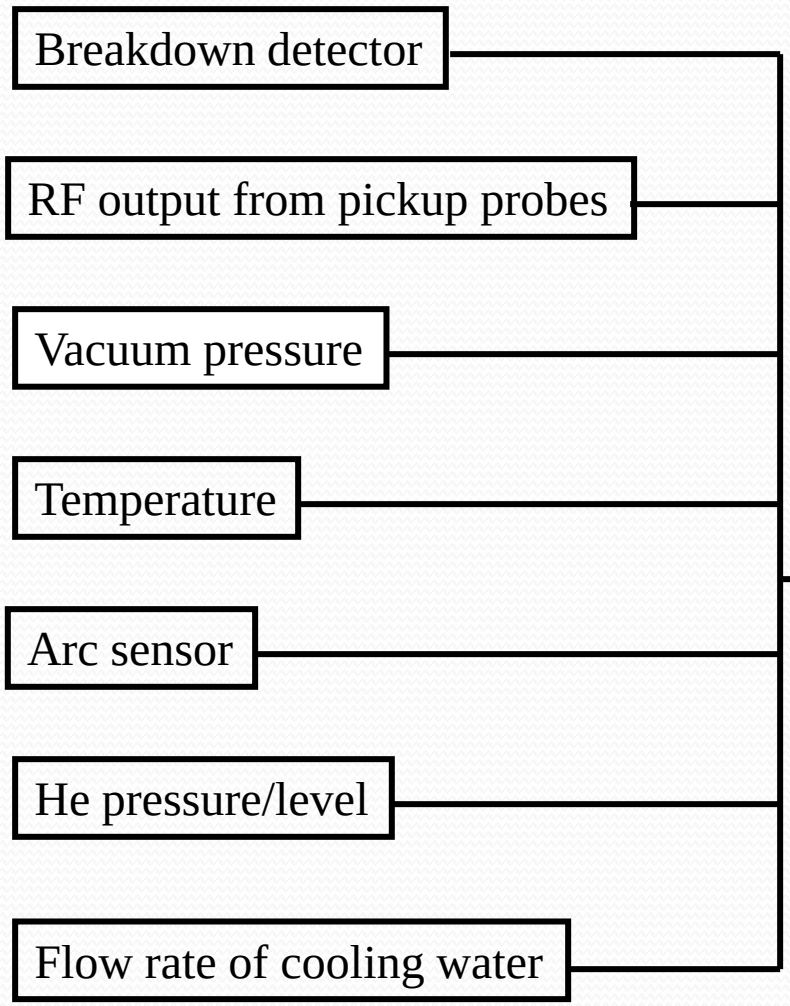


Mostly similar to the low level system for the SC accelerating cavities.

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

Crab cavity I/L system

IL system is important to protect the hardware



Breakdown detector judges whether P_{kly}, V_C and φ_{crab} are normal, or not.
If not, Crab RF is switched off.
This is the most frequent cause of Crab RF trip.

Several pickup probes are attached for monitoring the transmit power and the RF output at coaxial beam pipe.

Crab RF Off → Beam abort

Whenever Crab RF is switched off, the beam is aborted immediately.

Cavity conditioning

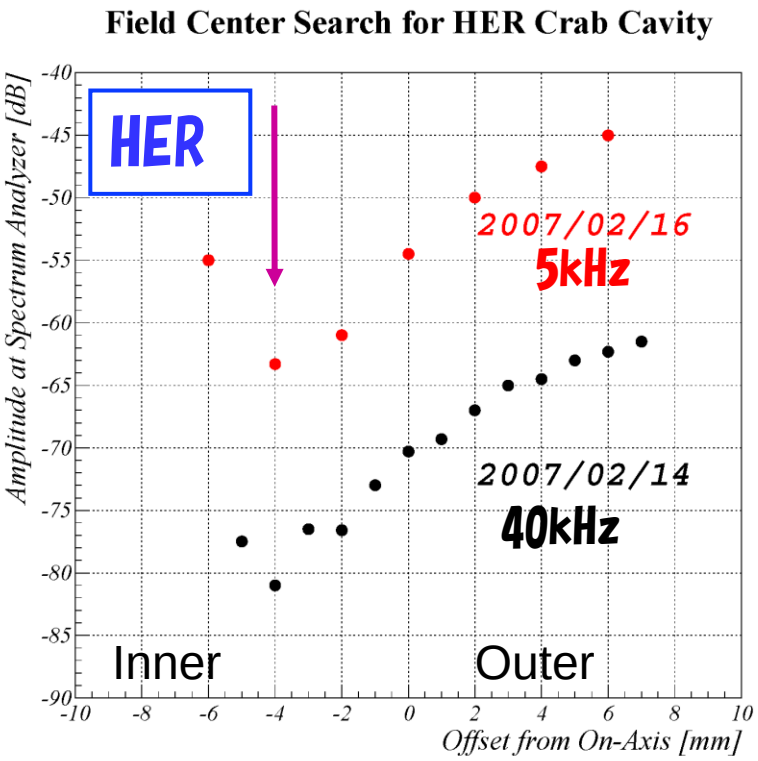
- Coupler conditioning before cooldown
  - Up to 200 kW SW
- Cool down
  - 2K/H for ~1 week
- Frequency tuner setting
  - 3 days
- Cavity conditioning
  - ~1W
  - HER crab up to 1.7 MV
  - LER crab up to 1.6 MV

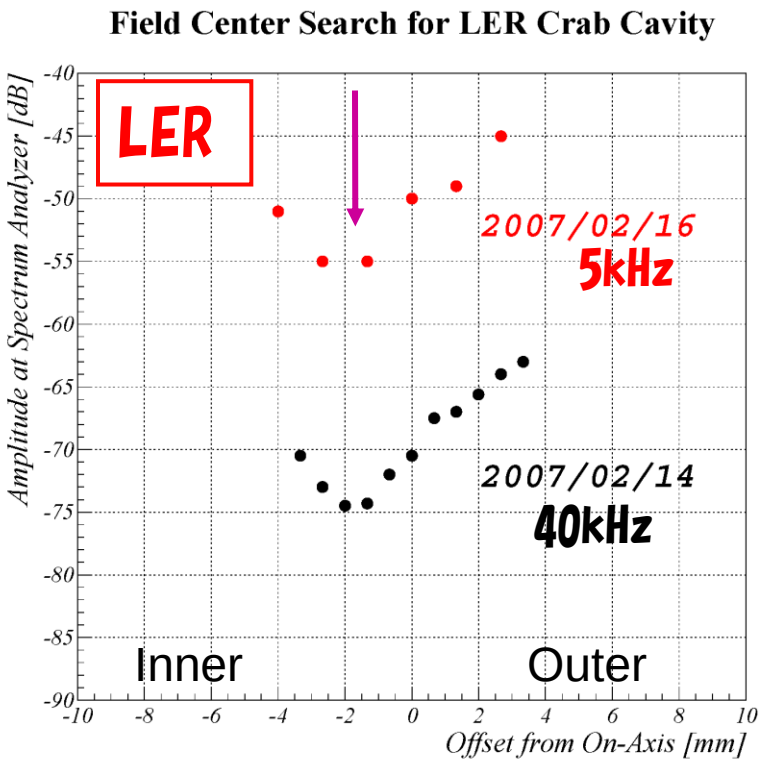
Cavity tuning with beams

- Search for the field center in the cavity (beam-induced power)
- Search for the crabbing phase and calibration of the crabbing voltage (closed orbit distortion)
- Phase stability
  - Tuner mechanism problem of LER crab cavity
  - Tuner phase stability
  - Crab phase stability

Search for field center in crab cavity

A local bump orbit was set with the crab cavity detuned





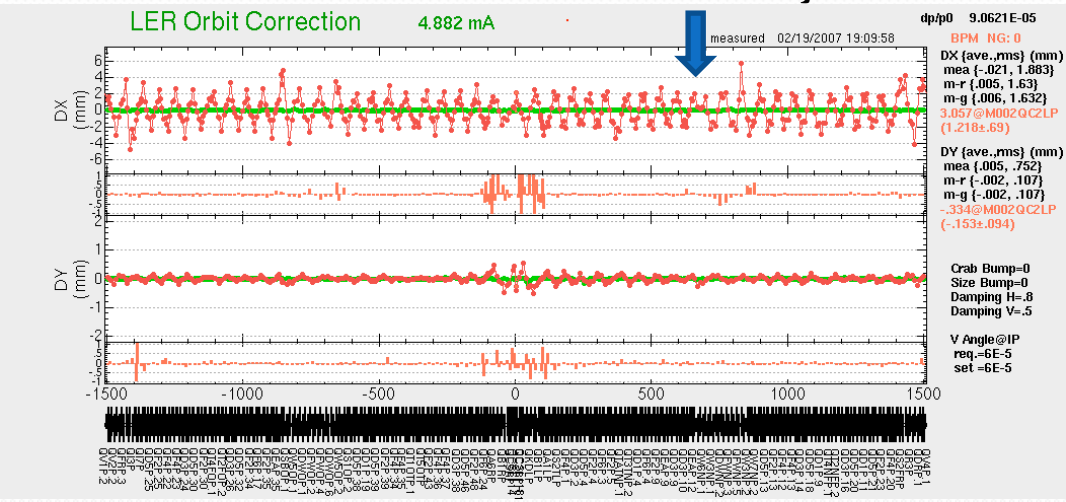
Field center search by measuring beam-induced crabbing mode
Crab cavities detuned by 5 kHz and 40 kHz.
Field centers given at the minimum induced voltage

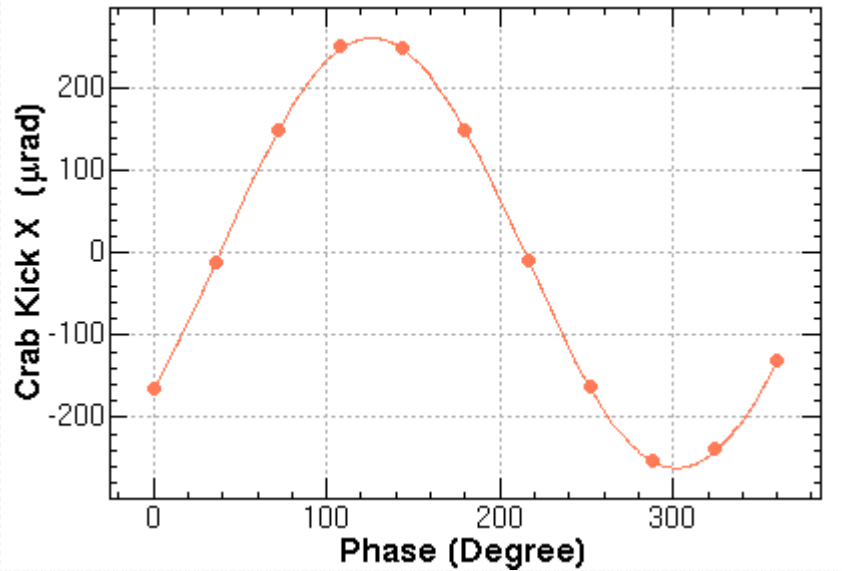
Search for the crabbing phase

- Horizontal orbit distortion by crab kick
- Crabbing phase determined at the minimum crab kick
  - Vc set: 1.0MV
  - Vc calibrated from this orbit distortion: 0.987MV

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

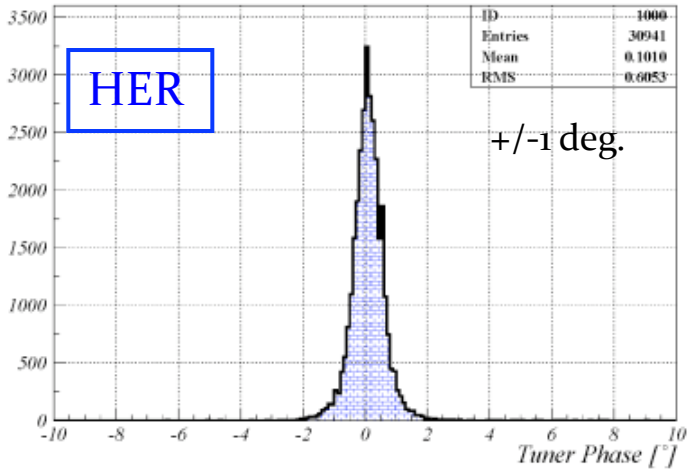
Crab cavity

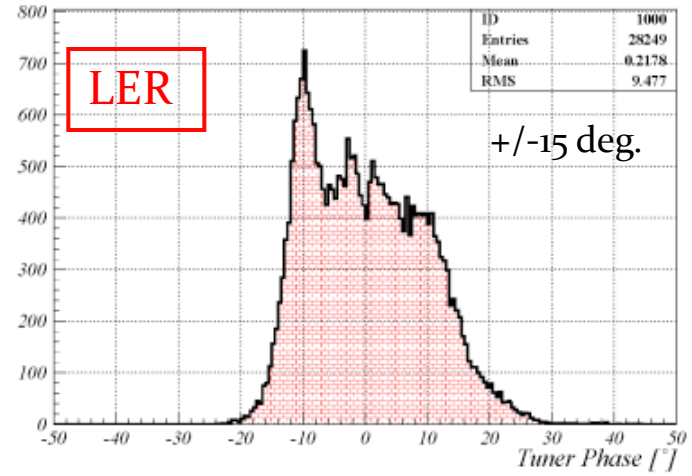


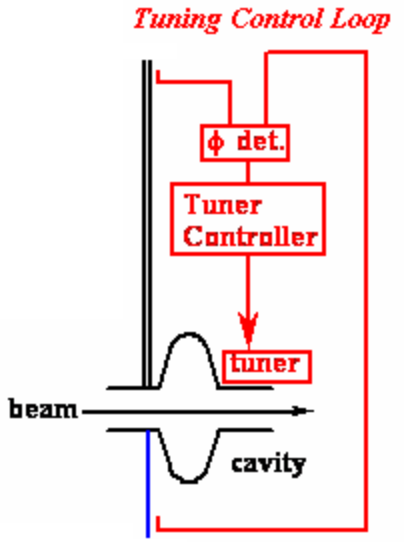


Tuner phase control

Distribution of tuner phase for Vc > 0.3 MV

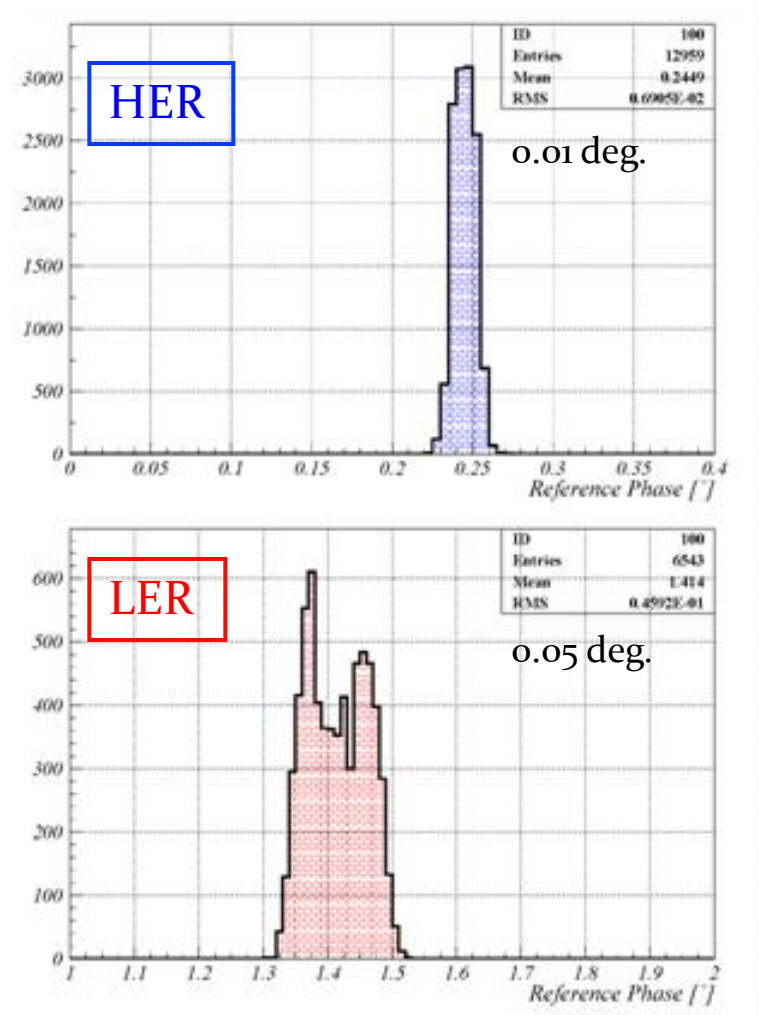


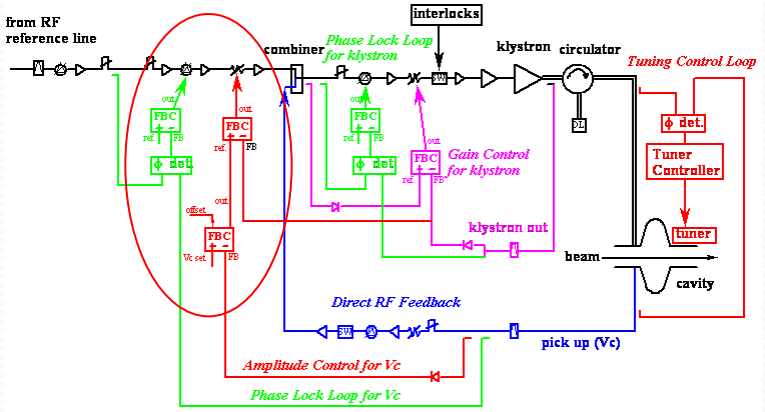




The HER frequency tuner is well controlled.
Tuning phase stays within +/- 1 deg.
The LER frequency tuner mechanism has a large backlash.
Tuning phase fluctuates about +/- 15 deg.

Crab phase control

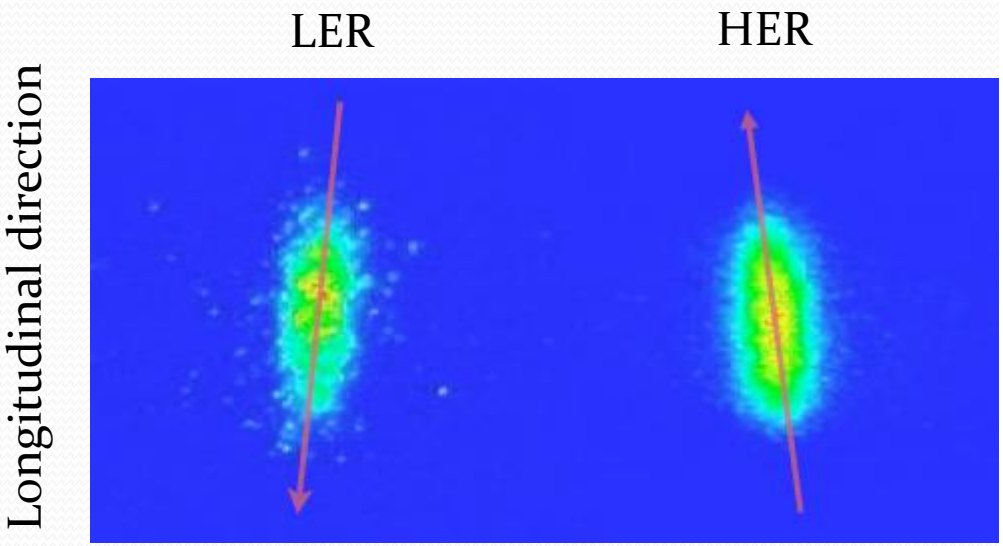


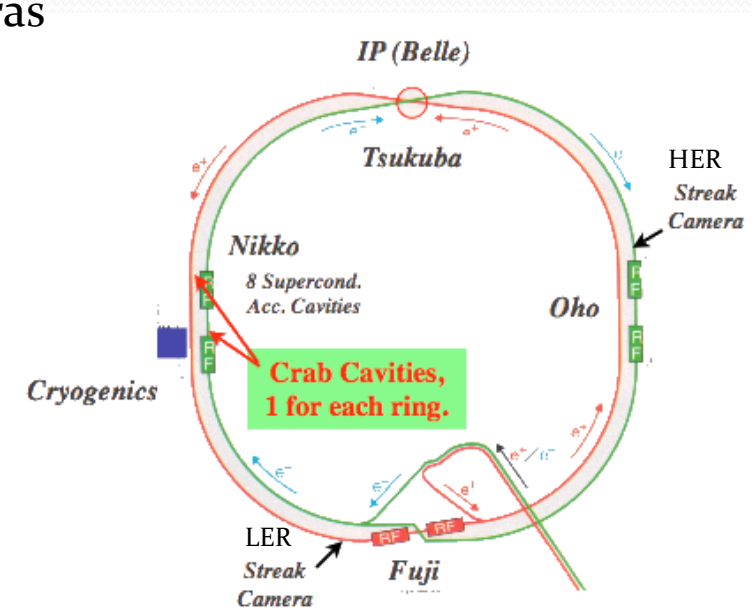


Low level feed back loops well stabilize the cavity voltage and phase.
Phase distributes within
0.01 deg. in the HER crab cavity,
0.05 deg. in the LER crab cavity.

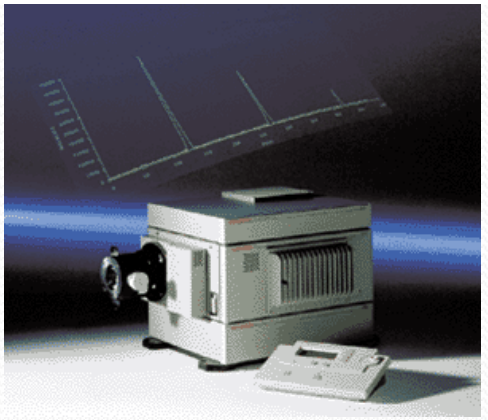
Observation with Streak Cameras

Bunch rotations were observed by two streak cameras





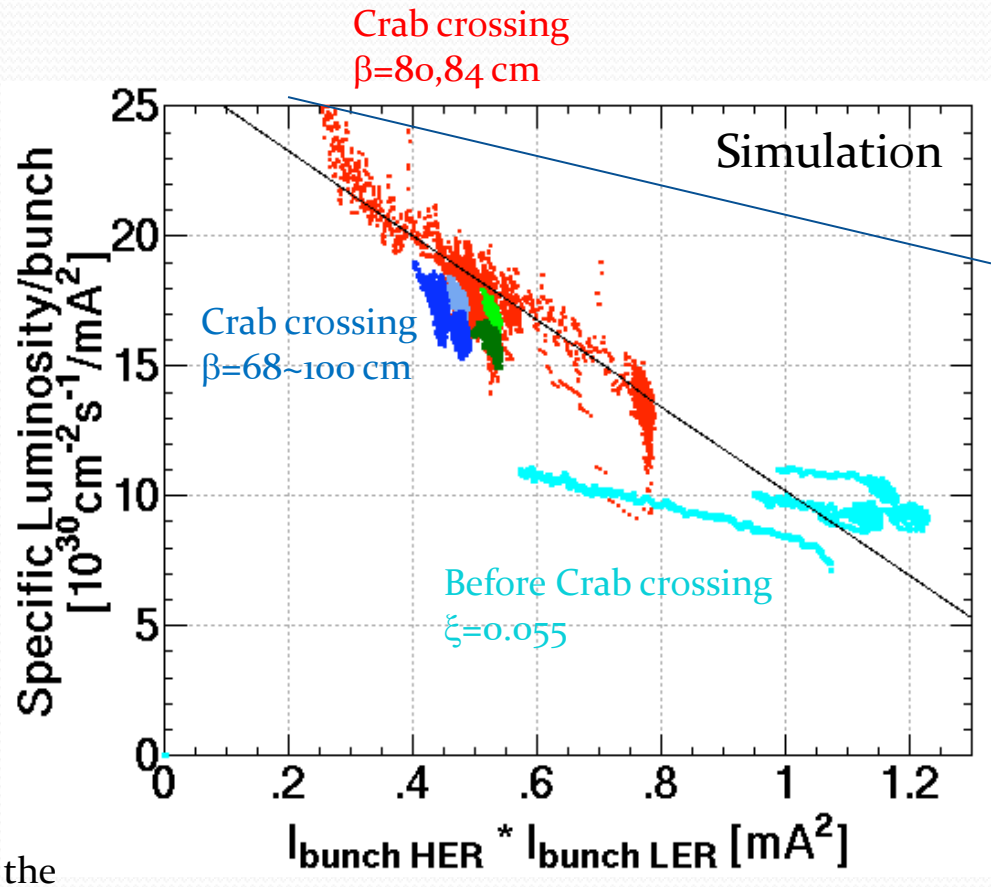
Beam bunches really tilted



Collision tuning at low current

$Lsp=L/(Ib_+Ib_-N_{bunch})$

- With crab crossing, specific luminosity / bunch was improved more than the geometrical gain
  - The vertical beam-beam parameter ξ became 0.088
  - It was 0.055 before the crab crossing
- Still lower than the prediction

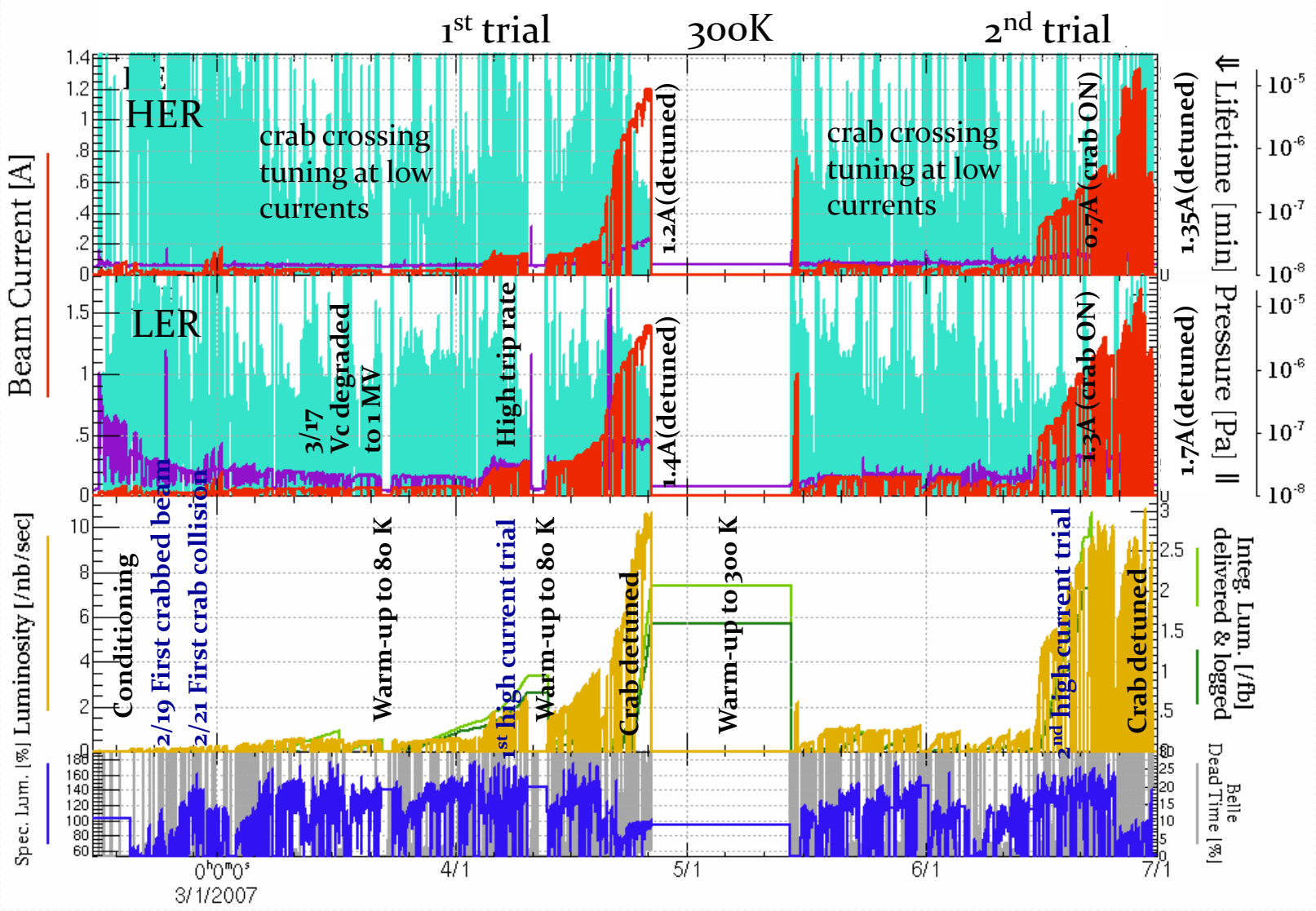


Remember that the crab crossing improves the luminosity reduction due to the geometrical overlap loss and also increase the beam-beam parameter

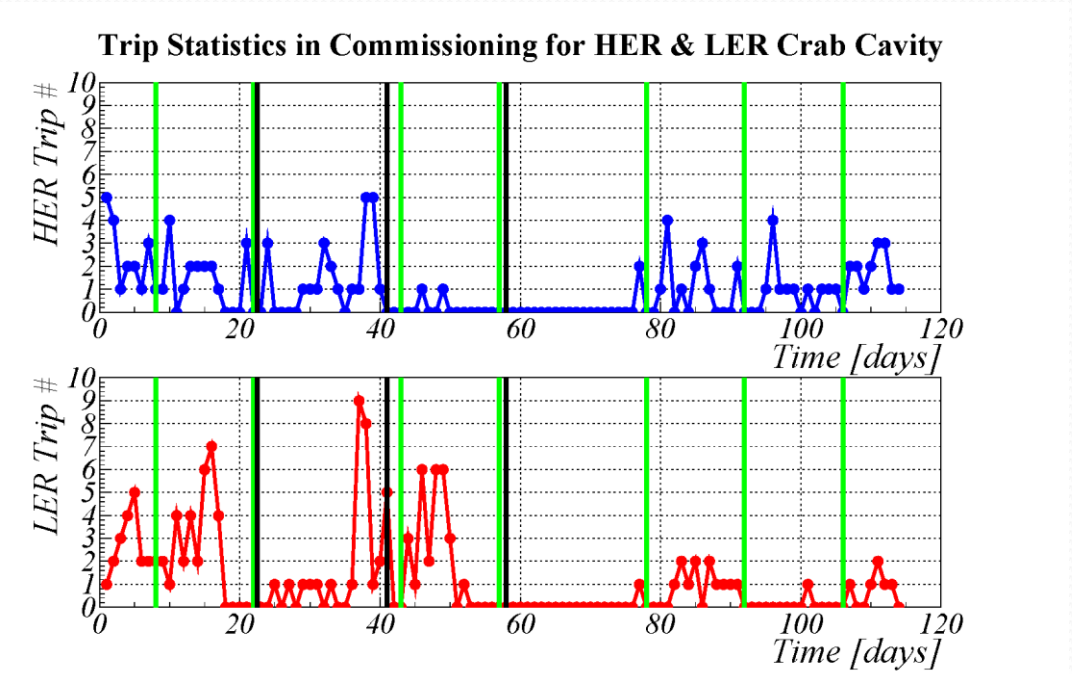
High current trial

- First trial with crab crossing was not successful
  - Vacuum pressure increased
  - Cavity trip rate increased
  - Warm up to 80K for evacuation
- Crab crossing suspended
  - Cavities detuned and scrubbing
  - Currents increased
    - LER:1.4A
    - HER:1.2A
  - Warm up to 300K
- Second trial with crab crossing
  - Stable vacuum pressure with crab crossing
  - Currents increased
    - LER:1.3A
    - HER:0.7A
- Current increase with crab cavities detuned
    - LER:1.7A
    - HER:1.35A

Overview of the crab commissioning (1st period)



Number of trips per cavity from Mar. 1 to Jun. 30



	LER	HER
Mar.	58	43
Apr.	55	21
May	13	16
June	12	32
Total	137	112
Rate	1.56	1.27

Green line: maintenance day

Machine maintenance in a day shift

Conditioning of crab cavities

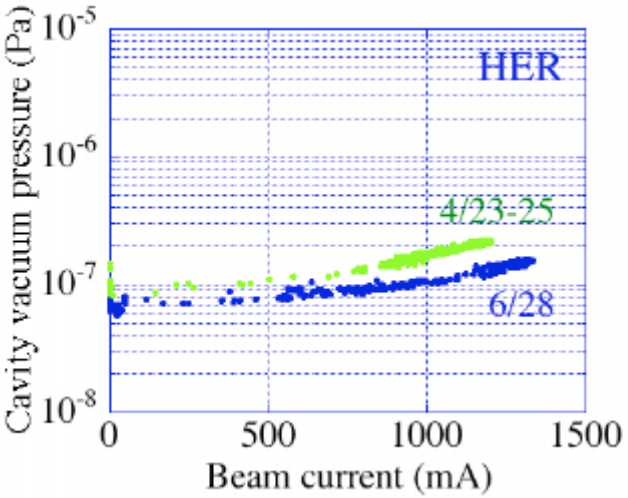
Black line: warm-up

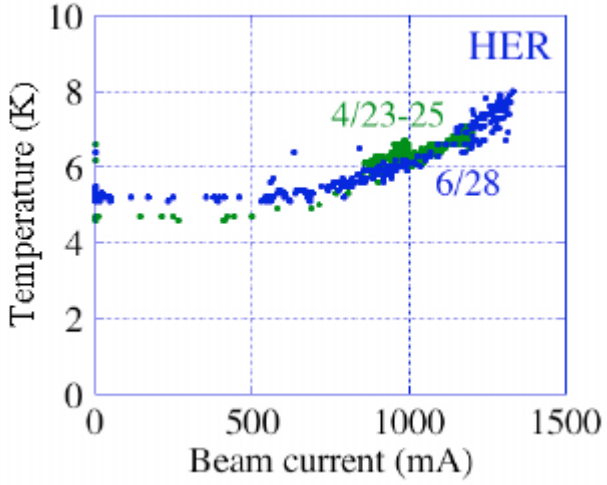
First two: up to 80K for one day

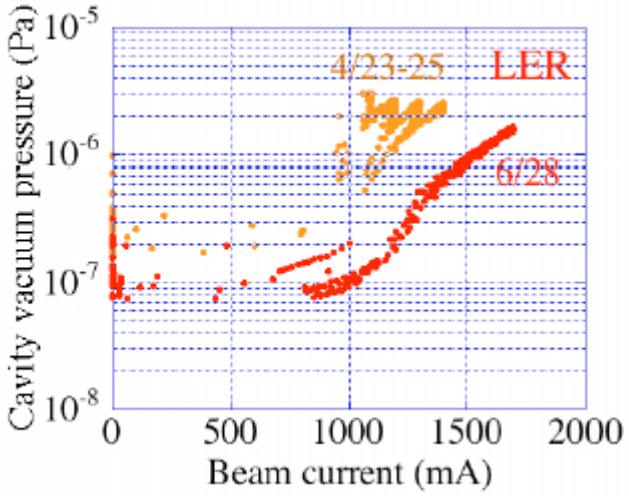
Third: up to 300K for about three weeks

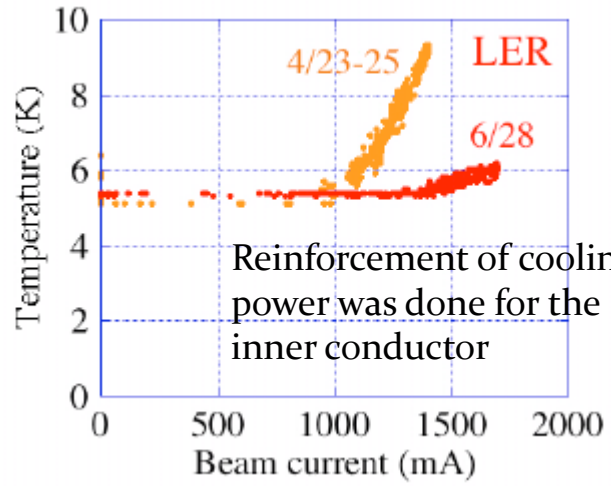
Improvements of vacuum pressure after warm-up

Vacuum pressure in each cavity improved after vacuum scrubbing and warmup to 300K









Reinforcement of cooling power was done for the LER inner conductor

Achieved parameters and problems during commissioning

- Achieved parameters
- LER voltage drop
- LER Tuner problem
- Phase stability
- Voltage oscillation at high current crabbing beams

Achieved parameters

	LER	HER
Beam current (Crabbing) (mA)	1620	850
Beam current (Crab detuned) (mA)	1700	1350
Maximum crabbing voltage (MV)	1.6→1.3→1.1	1.8
Operating crab voltage (MV)	0.8～0.95	1.3~1.48
Ferrite HOM damper load(kW)	12	12
Tuner phase (deg.)	±13	±1
Tuner phase w/o piezo (deg.)	±15	±3
Crab phase (deg.)	±0.1	±0.1
Trip rate	1.6	1.3

Crabbing voltage

- HER crab cavity
  - Maintained high crabbing voltage around 1.45 MV
  - Sometimes raised up to 1.7MV to search the best crabbing angle
- LER Crab cavity
  - Degraded from 1.6 to 1.3 MV shortly after the startup
  - Further degraded to 1.0 MV after a heavy quench on Mar. 17, 2007
  - Slight recovery to 1.1 MV after warm-up to 80 K
  - Crabbing angle kept at 11 mrad by increasing the beta function from 40 to 80 m

Frequency tuner problems

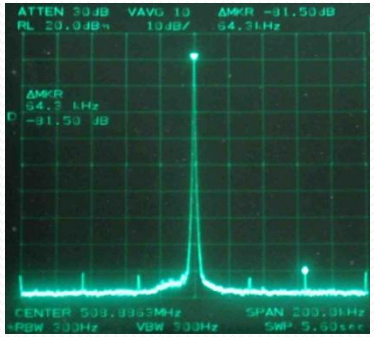
- The LER tuner has large backlash behavior
  - Tuner phase fluctuates +/- 15 deg.
- Piezo actuator broke down
  - Frequency tuner operates w/o piezo actuator
  - Tuner phase fluctuation increased +/-2 deg.
- LLRF still well controls crabbing phase even with large tuner phase fluctuation

Phase stability

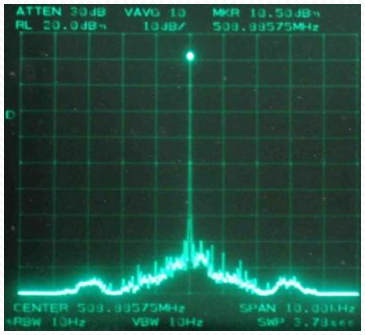
- Spectrum of pick up signal was analyzed and consistent with phase detector data.
- Phase fluctuation faster than 1 kHz is less than $\pm$ 0.01° , and slow fluctuation from ten to several hundreds of hertz is about $\pm$ 0.1° .
- They are much less than the allowed phase error obtained from the beam-beam simulations for the crabbing beams in KEKB.

K. Akai

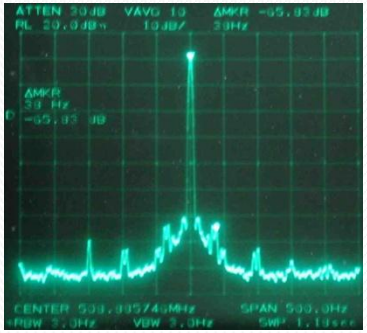
According to b-b simulation by Ohmi-san, allowed phase error for N-turn correlation is $0.1\times\sqrt{N}$ (degree).



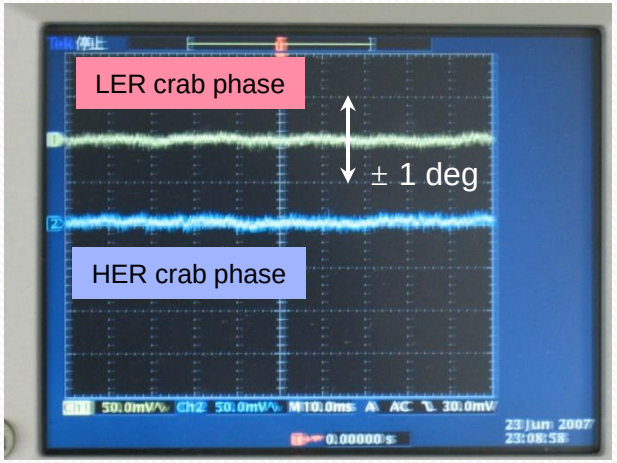
Span 200 kHz
Sideband peaks at 32kHz and 64kHz.



Span 10 kHz



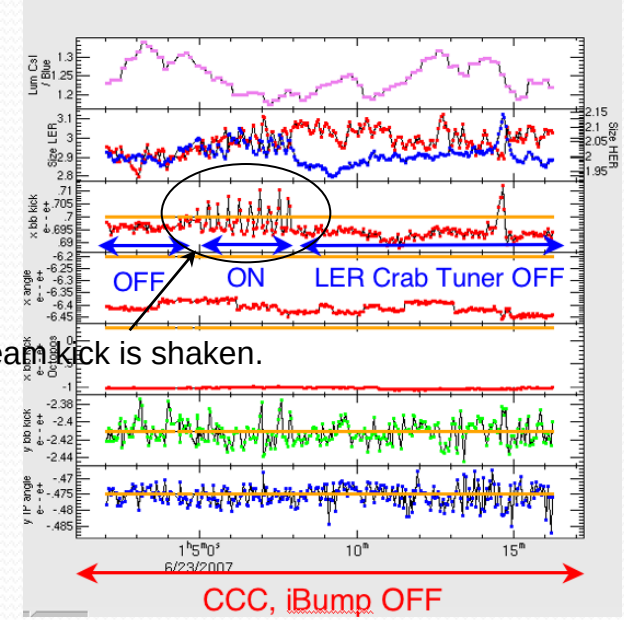
Span 500 Hz
Sideband peaks at 32, 37, 46, 50, 100 Hz.

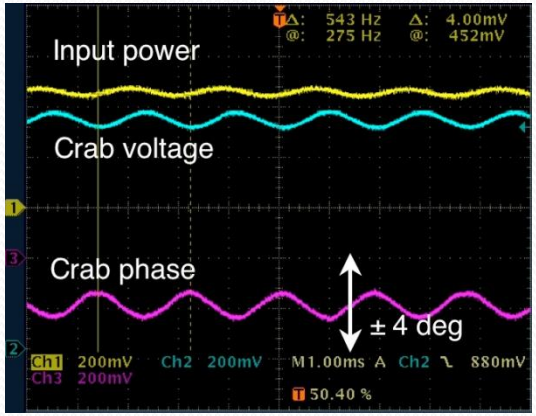


Phase detector signal. Beam current was 385mA (HER) and 600 mA (LER).

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

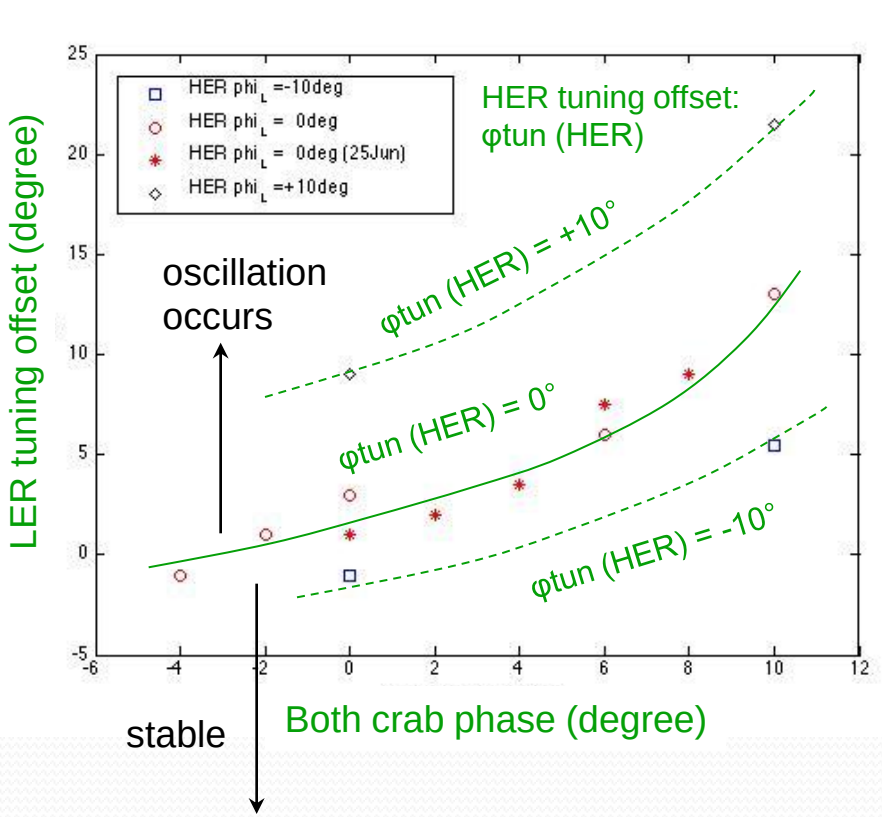
Oscillation of high-current crabbing beams





- 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.
- We found that it can be avoided by shifting the crabbing phase by +10° and controlling the tuning offset angle appropriately.

Tuning offset +5° (HER), -8° (LER)
Crab phase: +10° (HER/LER)

Crab cavity operation

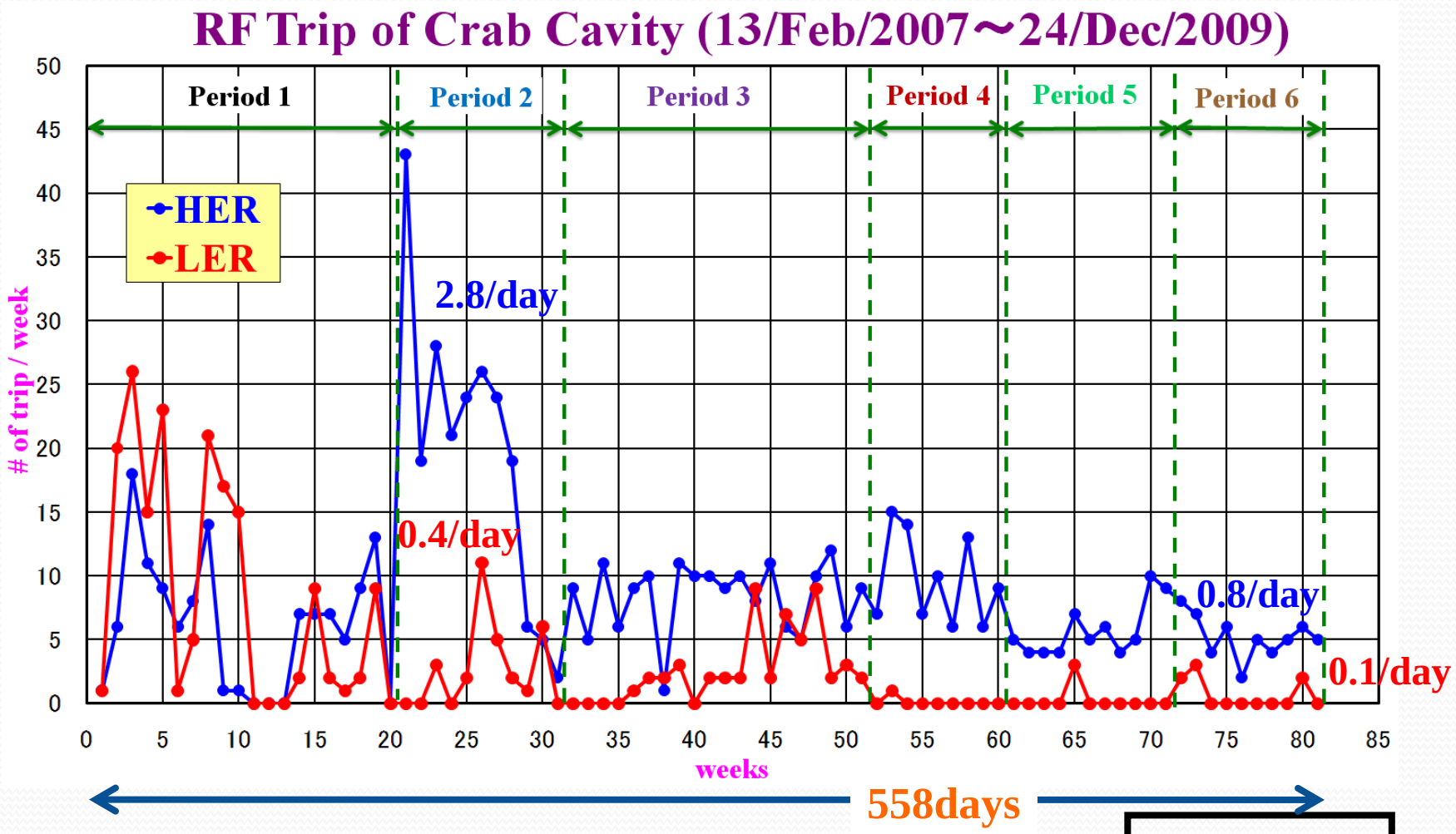
- Brief history
- Trip rate
- Breakdown of piezo actuator
- Cavity voltage
  - Degradation
  - Voltage scanning
  - Voltage oscillation and its remedy
- Beam-induced RF spectrum
- HOM loads
- Need for higher voltage
  - Effort to cool down below 4K

Brief history

month/year	comments
Jan/2007	Crab cavities were installed into KEKB.
Feb/2007	Beam commissioning started with “Crab ON”.
Mar/2007	Cavity voltage of LER Crab dropped suddenly.
Jun/2007	Piezo actuator of LER Crab broke down for the first time. Oscillation was observed at high beam current with crabbing collision.
Oct/2007	Physics run started with “Crab ON”.
May/2008	Cavity voltage of LER Crab was recovered slightly.
Oct/2008	Lower temperature operation was tried to recover cavity voltage of LER Crab.
Mar/2009	Lower temperature operation was retried.
Oct/2009	Oscillation was observed again, regardless of setting tuning phase offset and crab phase.
Dec/2009	Beam current with “Crab ON” achieved 1250mA for HER and 1700mA for LER.

RF trip of crab cavity

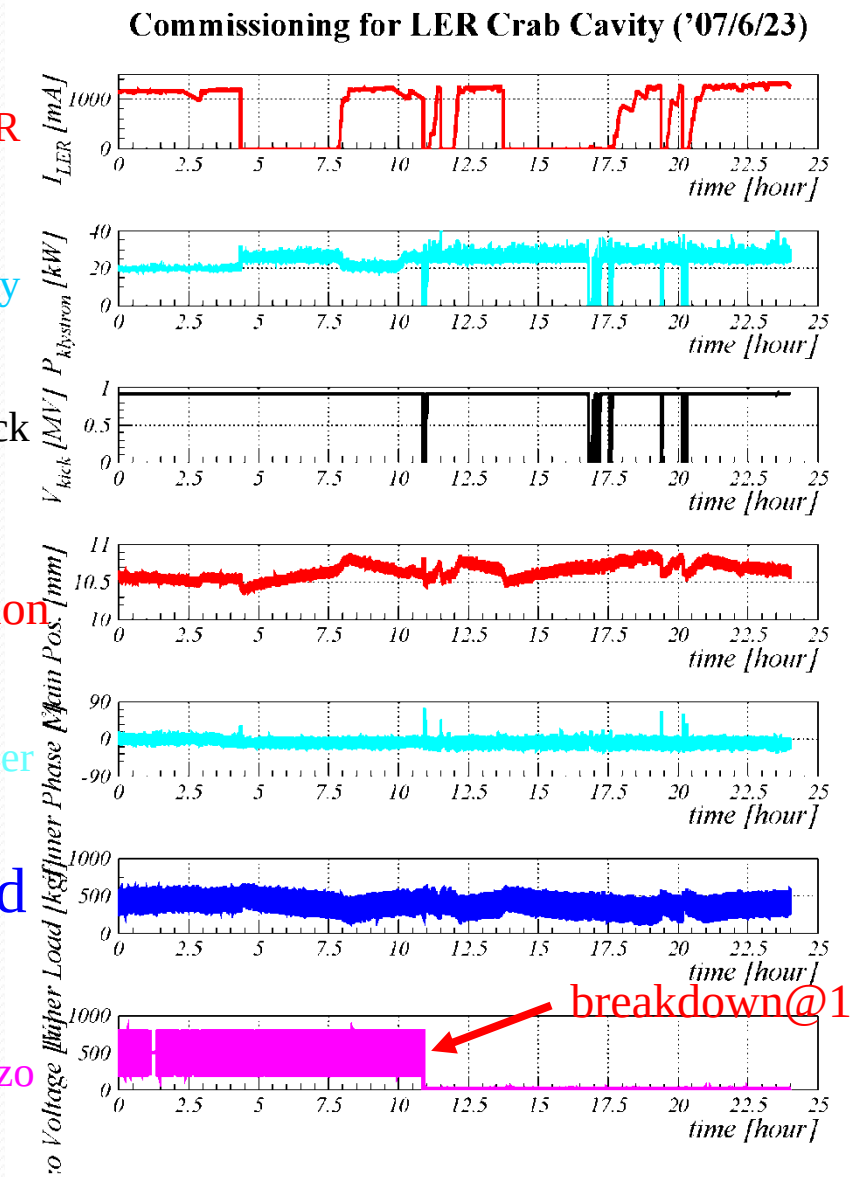
Period 1 : Feb/2007~Jun/2007
Period 2 : Oct/2007~Dec/2007
Period 3 : Feb/208~Jun/2008
Period 4 : Oct/2008~Dec/2008
Period 5 : Apr/2009~Jun/2009
Period 6 : Oct/2009~Dec/2009



Total average

HER : 1.3/day
LER : 0.5/day

Piezo actuator breakdown

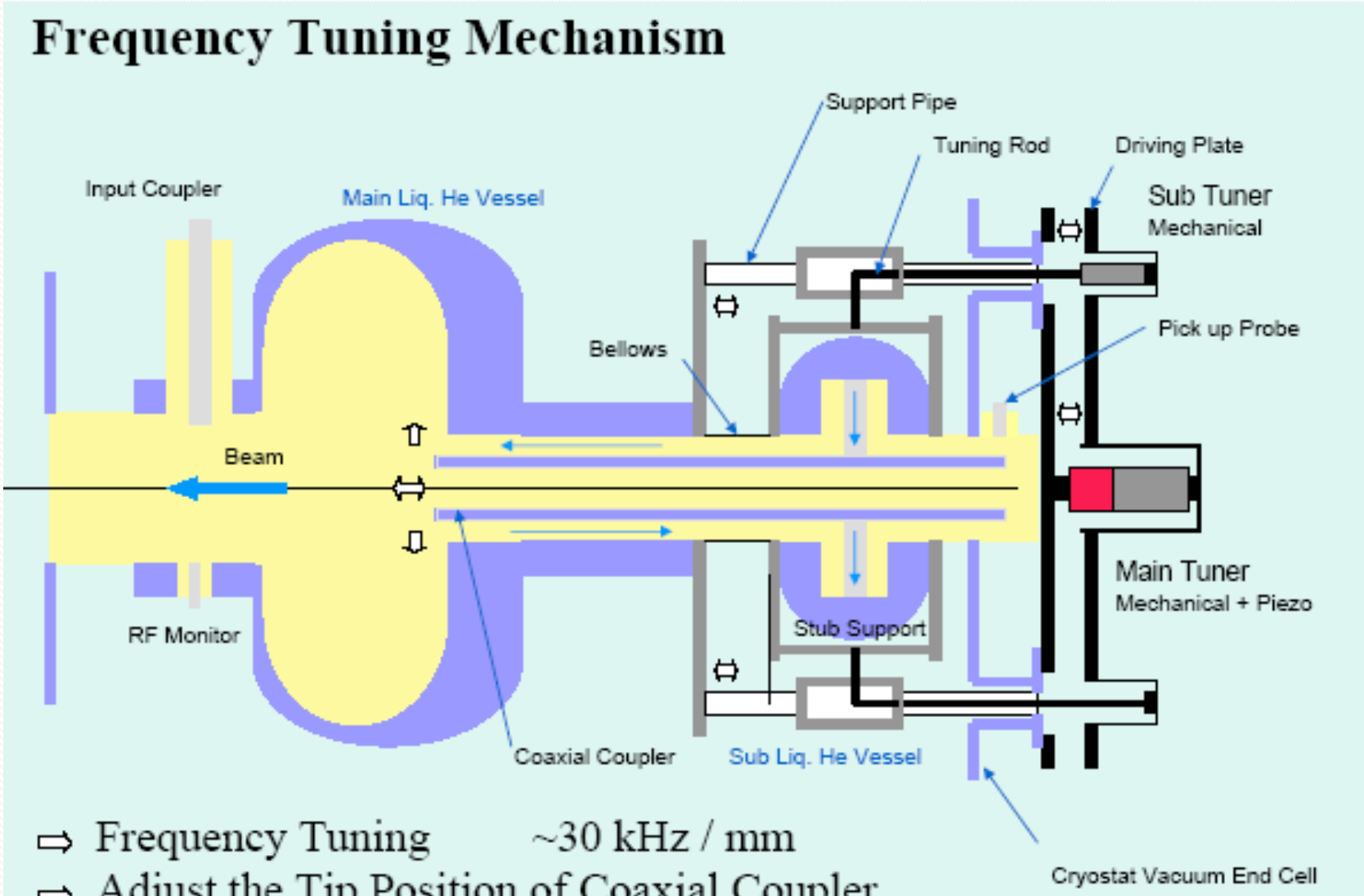


Date	Cavity	Comment
Jun/9/2007	LER	At RF recovery
Jun/23/2007	LER	At beam abort with RF trip
Oct/1/2007	HER	At RF recovery
Oct/4/2007	HER	At RF trip
Oct/16/2007	LER	At RF recovery
Oct/15/2008	HER	At RF trip
May/15/2009	LER	At beam abort with RF trip
Jun/11/2009	HER	At beam abort with RF trip
Oct/25/2009	LER	At beam abort with RF trip

Crab cavities have been operated without Piezo actuator during most of beam commissioning.

Low level feedback system can control Crab cavity without Piezo.

Frequency tuning



Cavity voltage drop of LER Crab

Cavity voltage of LER Crab was better than HER at horizontal test.
But, after installation to beam line, it dropped gradually.
And, it dropped suddenly from 1.3 to 1.0MV in Mar/17/2007.

Date	Cavity voltage [MV]	Comment
Dec/2006	1.9	Horizontal test
Feb/19/2007	1.5	At the beginning of beam commissioning
Feb/22/2007	1.3	Maintenance day
Mar/17/2007	1.0	Suddenly dropped
Mar/23/2007	1.1	After thermal cycle
May/22/2008	1.2	Slightly recovered
Jun/30/2008	1.3	After pulse conditioning
Dec/18/2009	1.3	No recovery afterwards

Crab voltage scanning

Date	LER [MV]	HER [MV]
Feb/29/2008	0.83 → 0.88	1.37 → 1.41
Mar/4/2008	0.88 → 0.88	1.37 → 1.38
Apr/5/2008	0.83 → 0.84	1.38 → 1.39
Apr/15/2008	0.84 → 0.85	1.39 → 1.40
Apr/25/2008	0.83 → 0.83	–
Jun/4/2008	0.83 → 0.85	1.45 → 1.46
Jun/18/2008	0.83 → 0.83	–
Oct/26/2008	0.85 → 0.83	1.37 → 1.34
Nov/22/2008	0.83 → 0.81	1.50 → 1.48
Dec/18/2008	0.81 → 0.84	–
Apr/26/2009	0.85 → 0.83	1.35 → 1.32
May/20/2009	0.83 → 0.85	1.32 → 1.33
Jun/6/2009	0.85 → 0.86	1.33 → 1.37
Jun/18/2009	0.95 → 0.98	1.50 → 1.55
Nov/2/2009	0.87 → 0.90	1.29 → 1.34
Dec/12/2009	0.95 → 0.97	1.40 → 1.45

Voltage scanning is sometimes carried out as part of beam tuning for higher luminosity.

During this operation, RF trip of Crab cavity occurs frequently.

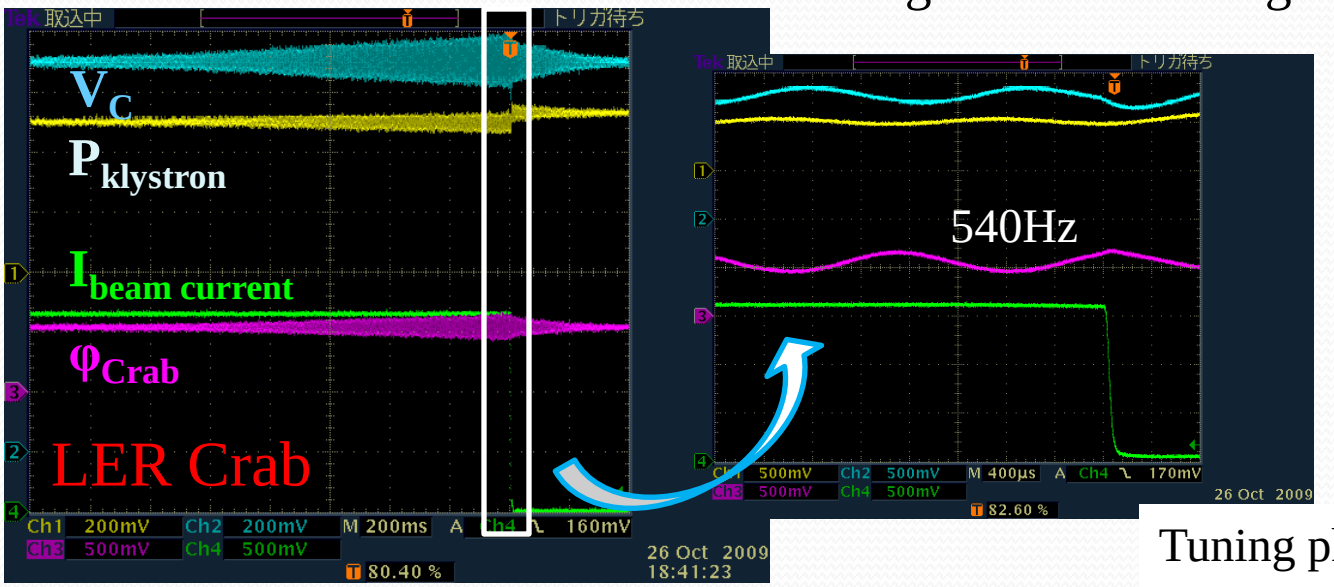
Very careful operation is necessary!

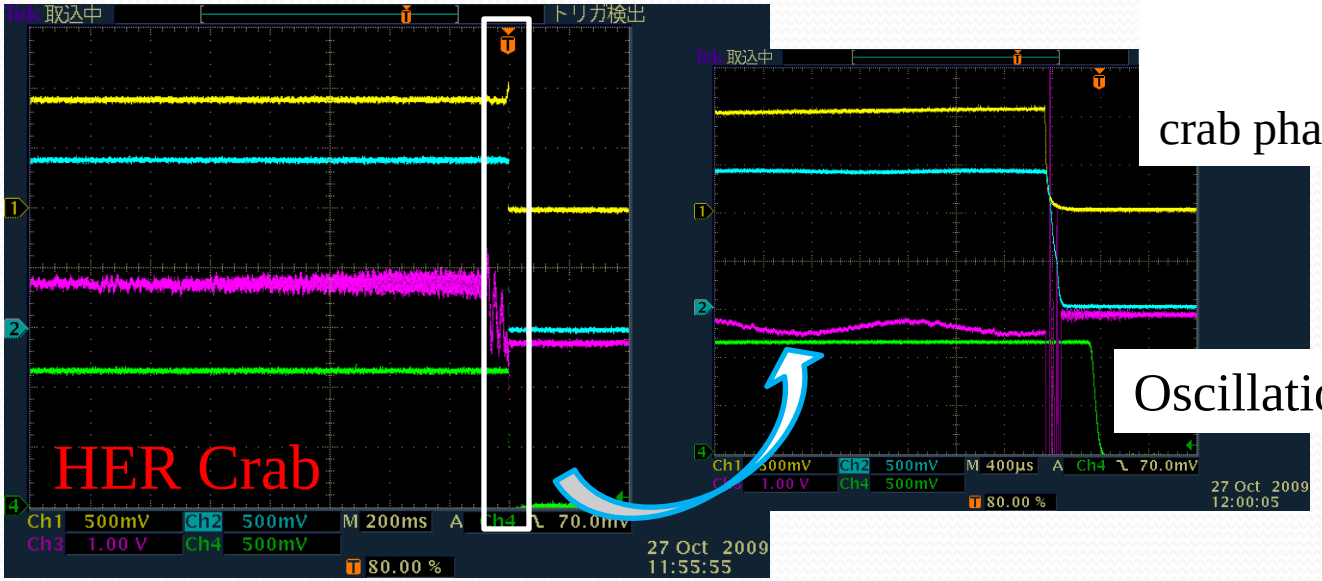
When Crab RF is switched off, RF conditioning is sometimes done at local control room.

Max. operation voltage

Oscillation at high beam current with "crab on"

Oscillation occurred again in autumn/2009, regardless of setting same values as previous.





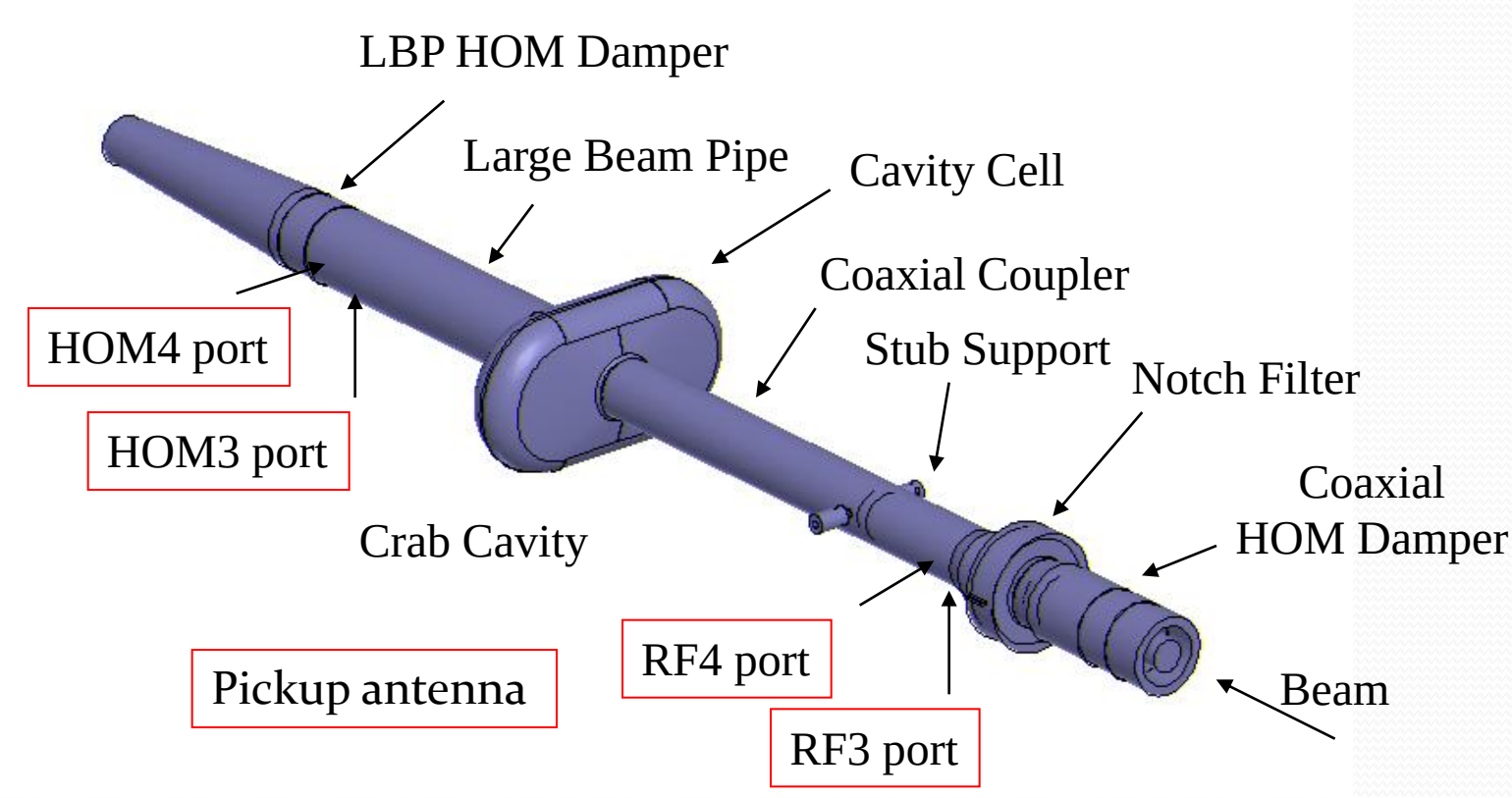
Tuning phase offset : +15° (HER)
–10° (LER)

crab phase : ~+19° (HER/LER)

Oscillation is suppressed again!

Beam-Induced RF spectrum

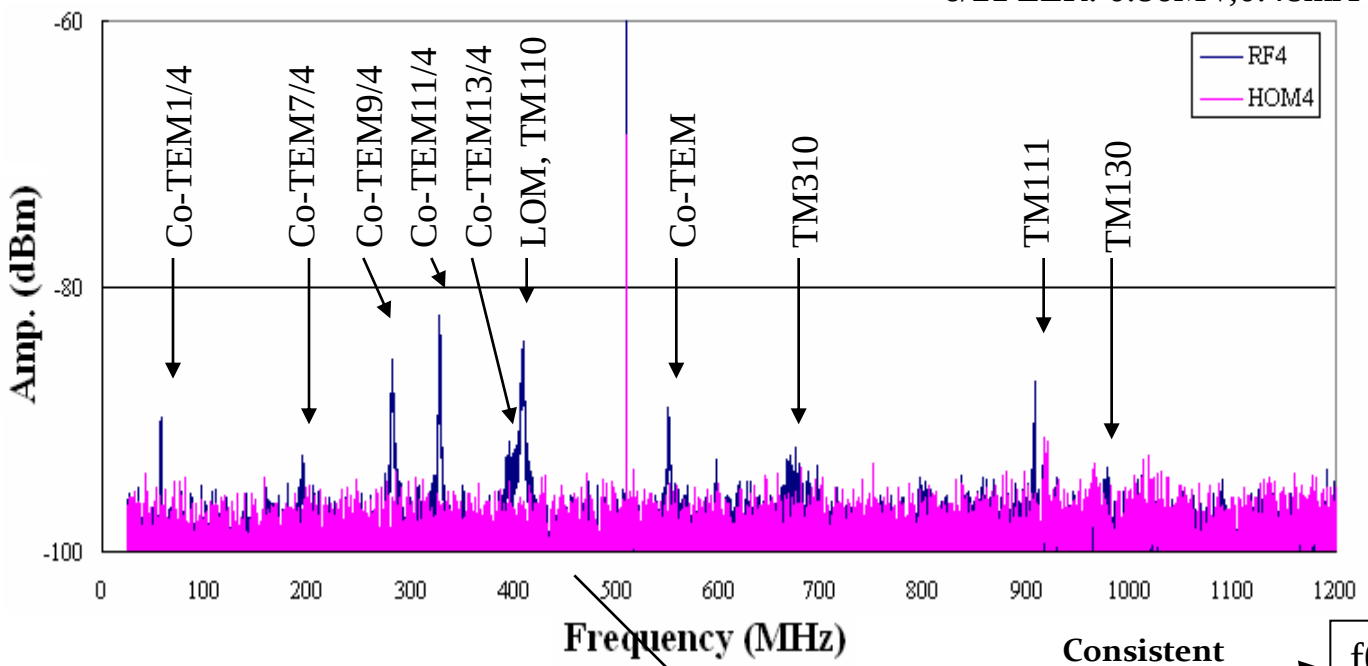
Crab cavity has several RF ports to measure beam-induced RF spectrum.
They are pick-up antennae.
Four antennae are set on the coaxial coupler.
Those antennae are suitable to measure HOM signals.
Four antennae are set on the beam pipe.
Those antennae are suitable to measure the beam spectrum



Single bunch operation at a machine study

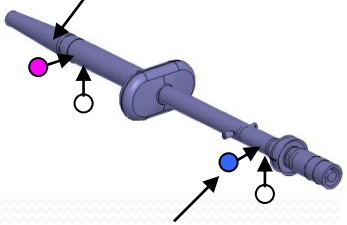
Single bunch operation is suitable to measure beam-induced RF modes since its beam spectrum is flat with a revolution interval (100 kHz)

6/21 LER: 0.86MV,0.48mA

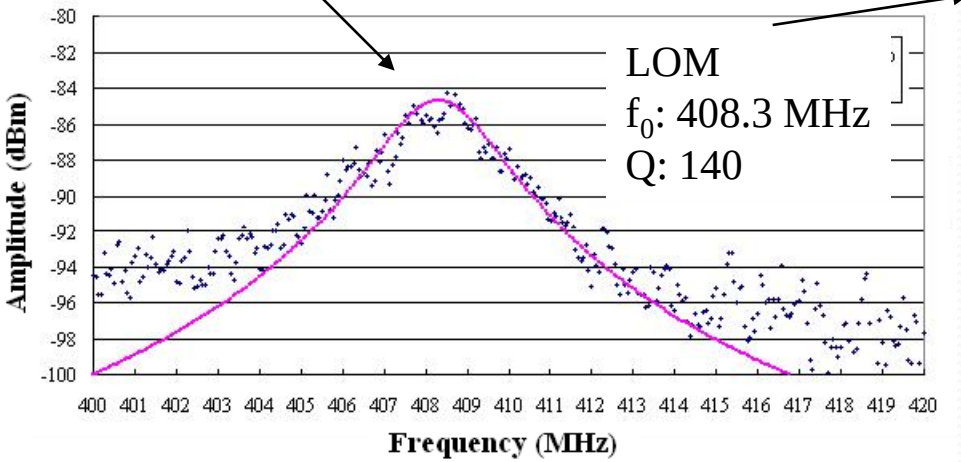


Freq(MHz)	Mode
56	co-TEM 1/4λ
195	co-TEM 7/4λ
282	co-TEM 9/4λ
327	co-TEM 11/4λ
395	co-TEM 13/4λ
408	TM110, LOM
550	co-TEM 19/4λ
672	TM310
696	TM310
907	TM111
979	TM130

Mainly observe beam spectrum.



Mainly observe beam-induced RF modes.



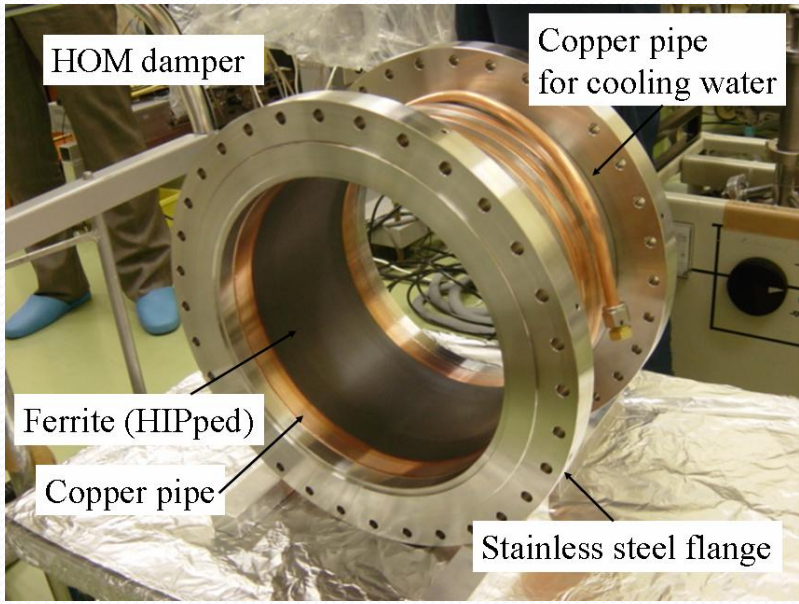
Consistent

f0: 408.3
Q: 140
Measured at horizontal test (@ room temperature)

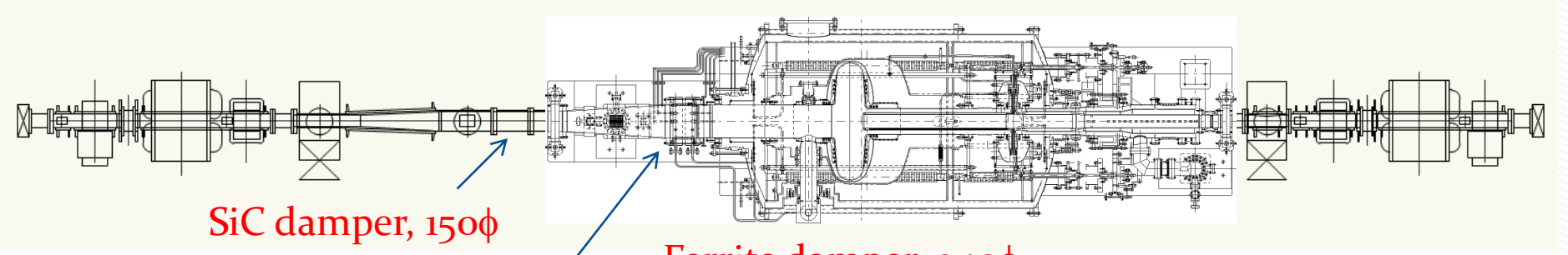
The most dangerous mode, TM110 (accelerating mode) is heavily damped.

HOM dampers

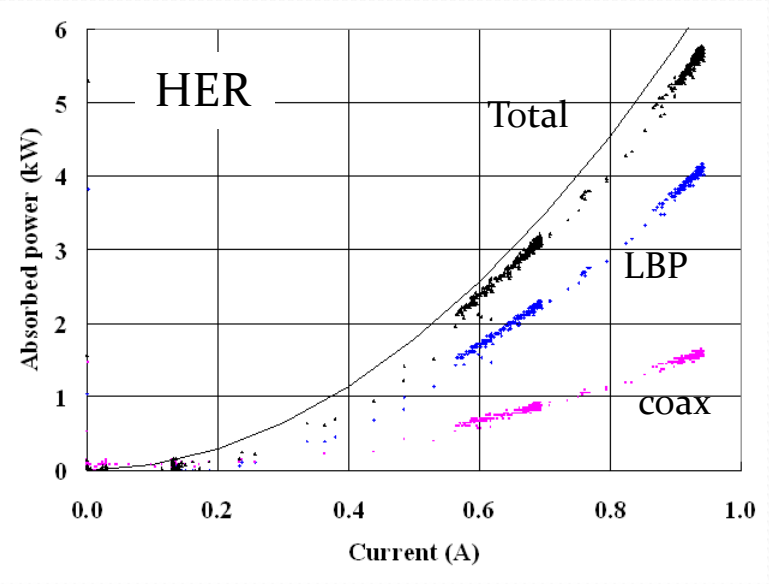
- Ferrite dampers
  - Beam pipe damper (LBP damper)
  - Coaxial damper (Coax damper)
  - Ferrite: 240mmϕ x 100mm x 4mm
- SiC damper
  - LER crab module has a SiC damper
    - SiC: 150mmϕ x 240 mm x 10 mm



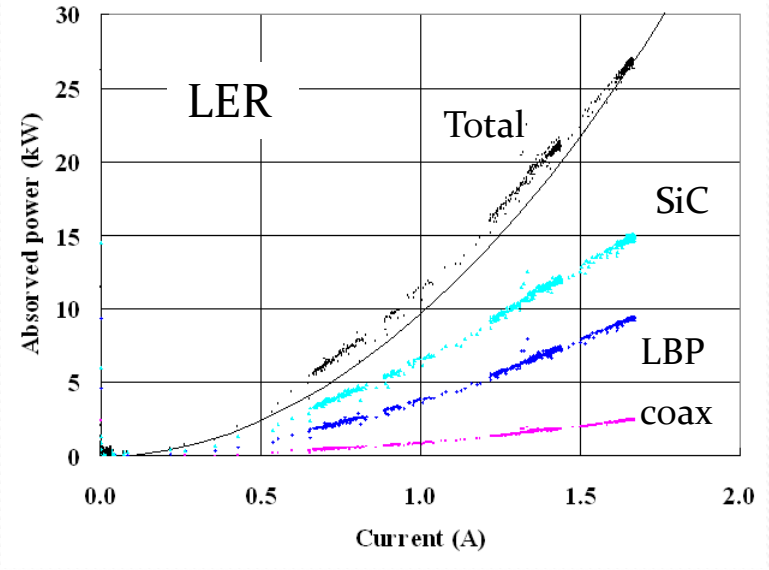
LER crab cavity module



Typical HOM powers in the beam operation



Absorbed HOM power:
4.1 kW (LBP) + 1.6 kW (coax) @ 0.95 A
Coax/LBP=0.4 for 3.06-sp, 1585 bunches
Calculation well reproduces total HOM power



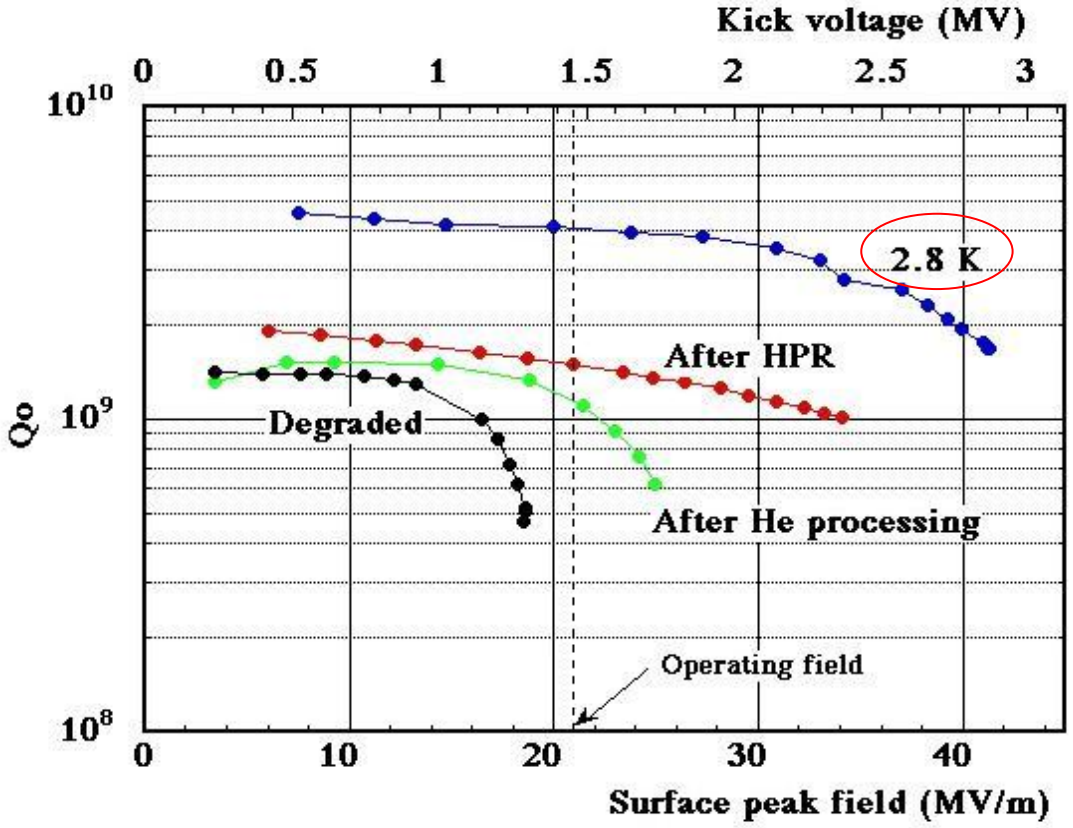
Absorbed HOM power:
9.4 kW (LBP) + 2.4 kW (coax) @ 1.62 A
Coax/LBP=0.25(LER) for 3.06-sp, 1585 bunches
SiC damper contributes for HOM power absorption.
Calculation well reproduces total HOM power

Need for higher Vc

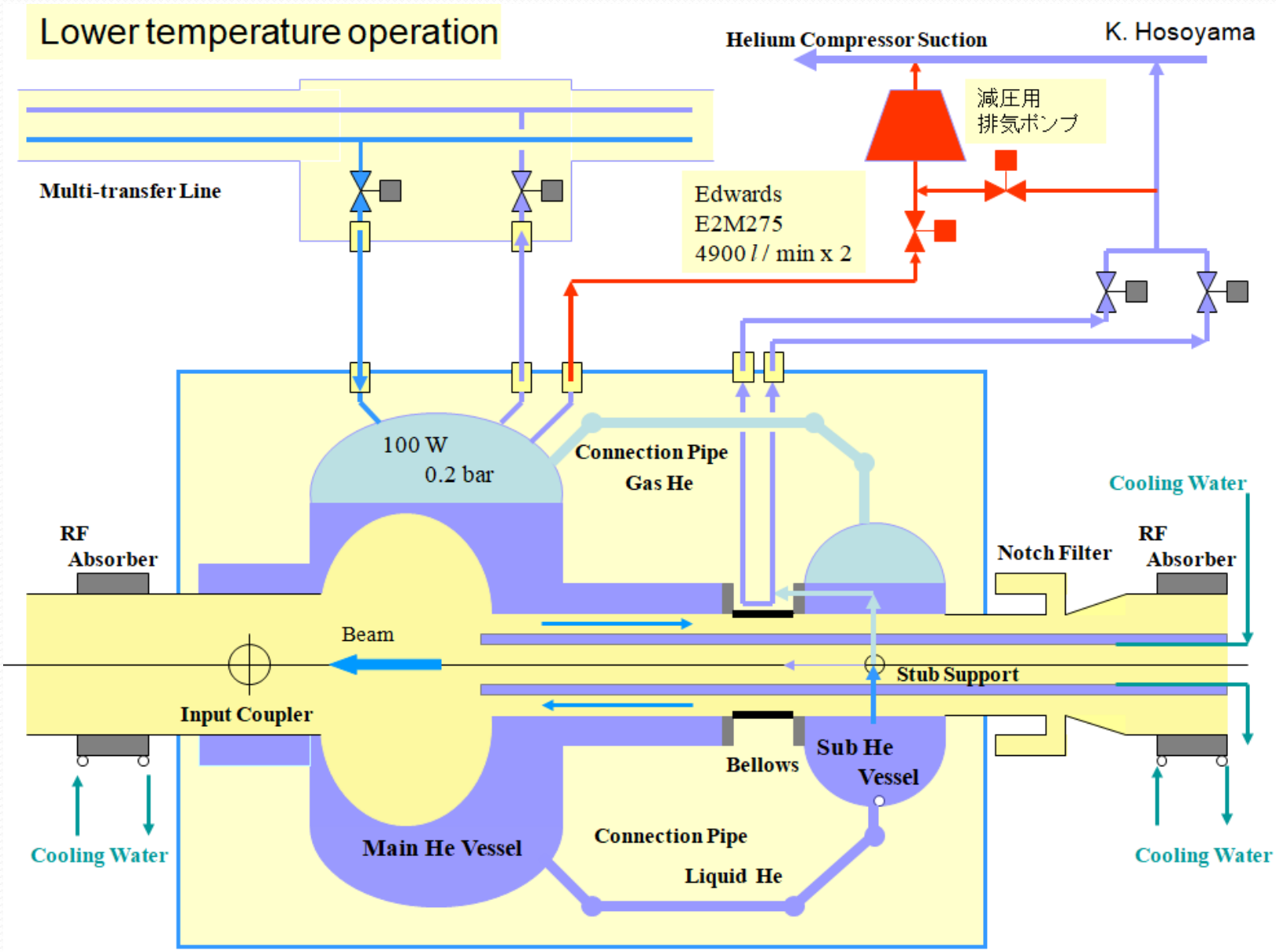
- Large beta function at crab cavity may cause beam loss.
- Physical aperture is ~100 mm.
- Higher Vc is required for low beta function
  - Low temperature operation below 4K may improve the Vc limit

Cavity performance at lower temperature

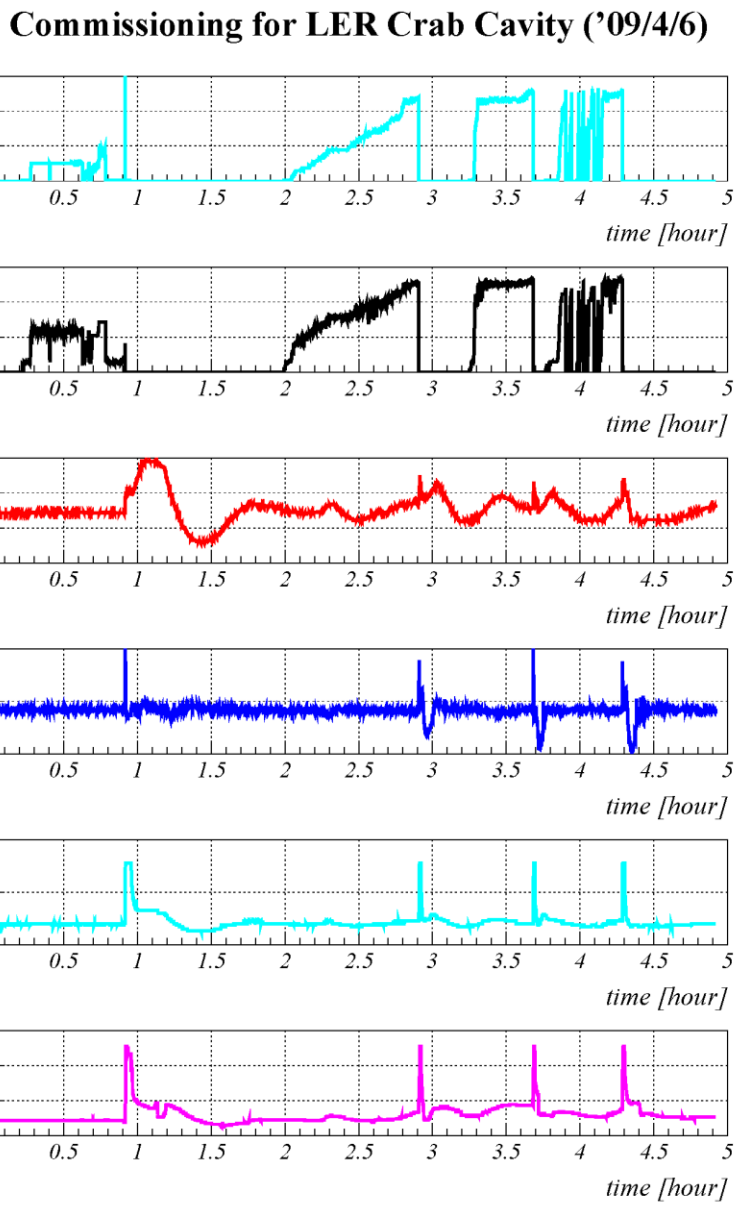
Vertical Cold Test (prototype cavity)



Lower temperature operation



Lower temperature operation



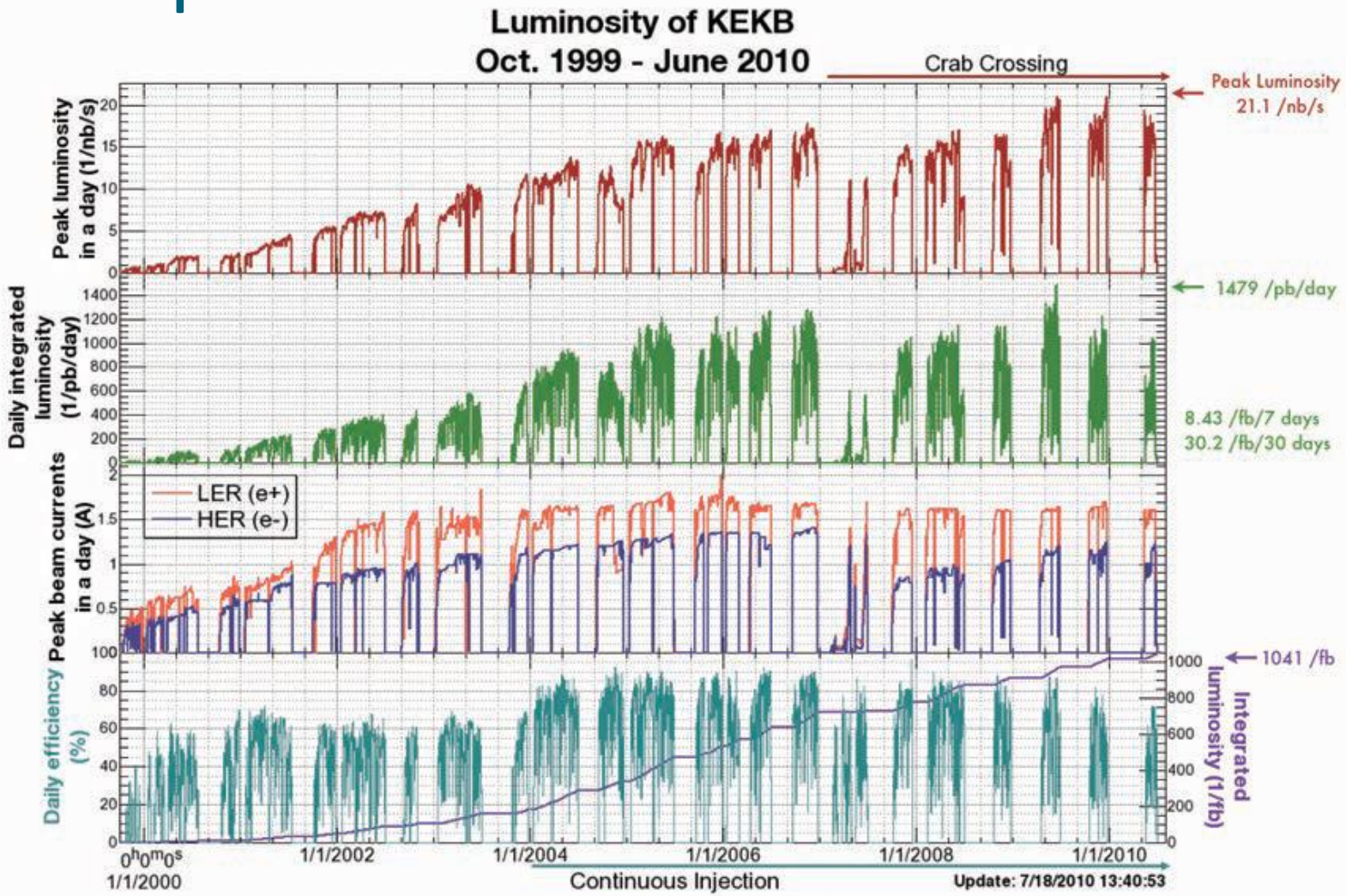
Lower temperature operation below 4K was tried.

The first trial was done in autumn/2008.
It failed due to unexpected oil reduction of the pumping system.

The second trial was done in spring/2009.
Lower temperature operation was successful!
The operation was stable around 3.6K.

But, performance of LER Crab cavity was not recovered.

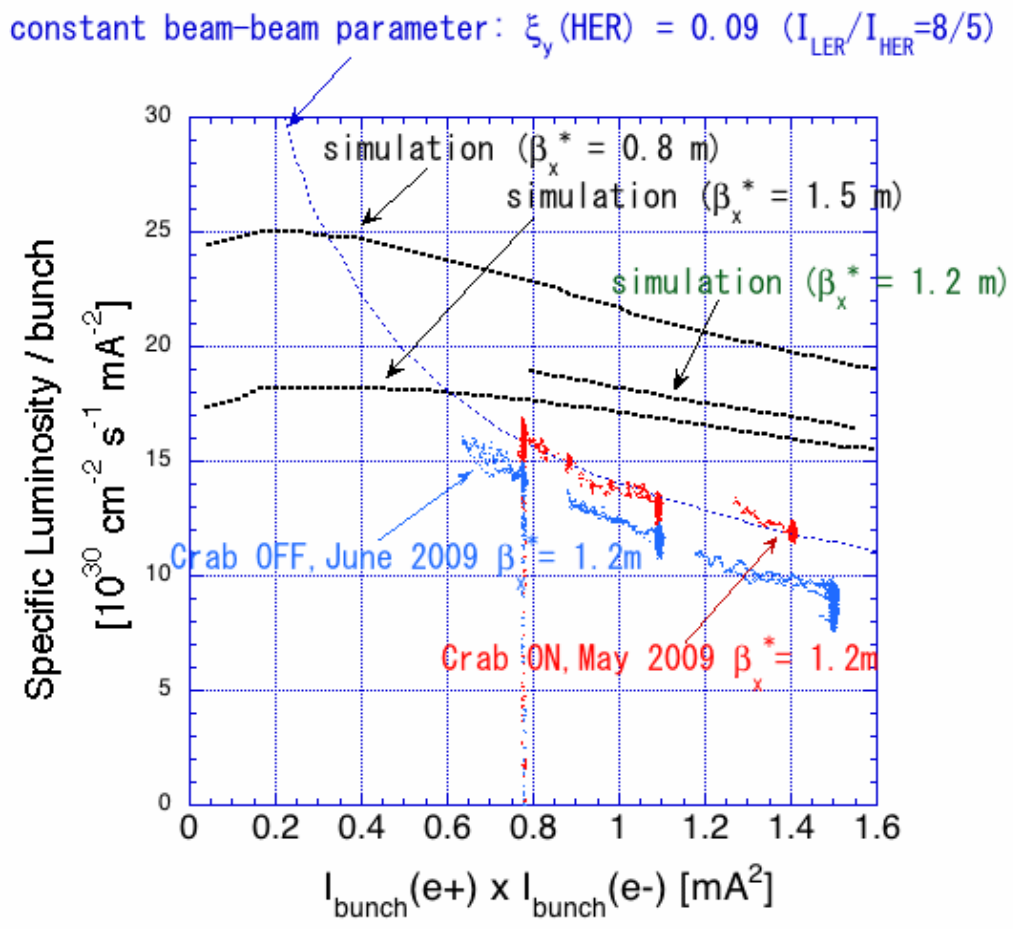
KEKB operation



Specific luminosity increase

Funakoshi

- Specific luminosity increase with crab crossing: 20 %
- More than geometrical reduction factor, 11%
- Beam-beam parameter:0.09
  - Improved from 0.057 w/o crab crossing
  - Still lower then the prediction



Achieved parameters

	LER	HER
Max. Beam current (mA)	1700	1238
Crab voltage (MV)	0.81~0.98	1.32~1.55
# of total trips	263	710
Average trip rate (in the last one year)	0.5(0.1)	1.3(0.8)
Max. HOM power (kW)	2.5+12.4+13.0+12.2 (Coax+LBP+SiC1+SiC2)	3.0+6.9 (Coax+LBP)

Another SiC damper added in 2009
HER LBP damper absorbed 9.9 kW at 1350A when crab detuned