Commissioning of Crab RF System

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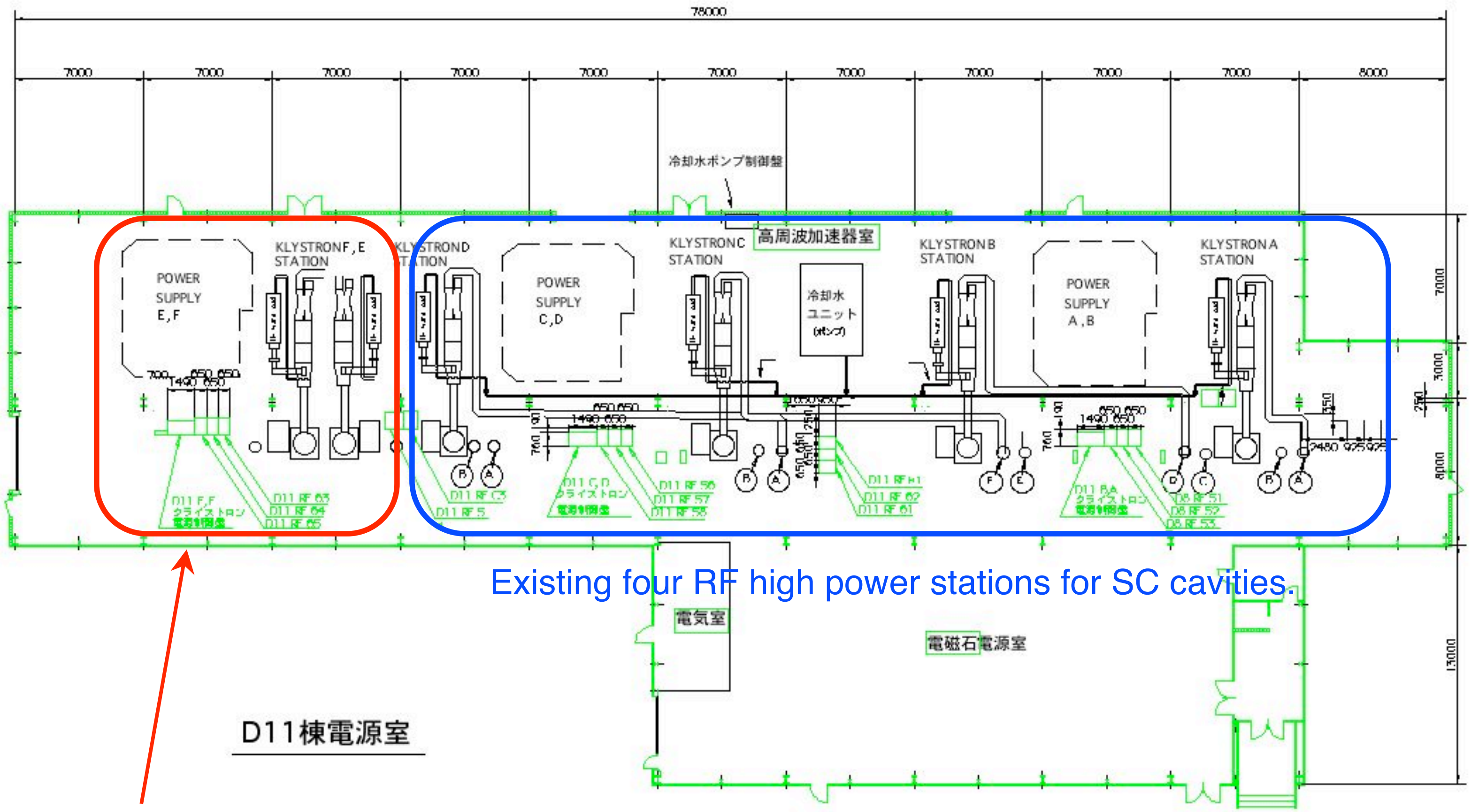
KEKB Review Committee

Construction and start up before beam commissioning

- Construction of two Crab RF stations (FY2004 ~):
  - Two reused klystrons, conditioned up to 600 kW, have been installed at D11-E and D11-F stations.
  - A spare power supply, modified to drive two klystrons, was moved from D2 to D11.
  - High power RF system including circulators, dummy loads, wave guides, and cooling system was completed.
  - Low-level RF control system as well as operation software has been completed.
- Start up of Crab RF system (Dec. 2006 ~):
  - System checking with high power RF source was done in Dec. 2006.
  - Wave guides were connected to crab cavities in Jan. 2007.
  - Conditioning couplers at room temperature was done in Jan. 2007.
  - Cavities were cooled down by a rate of -2K/hour. Reached to 4K on Feb. 4.
  - Adjustment of frequency tuners and alignment of coaxial pipe done on Feb. 5~8.
  - Final system adjustment and cavity conditioning started on Feb. 9.

Layout of D11 klystron gallery



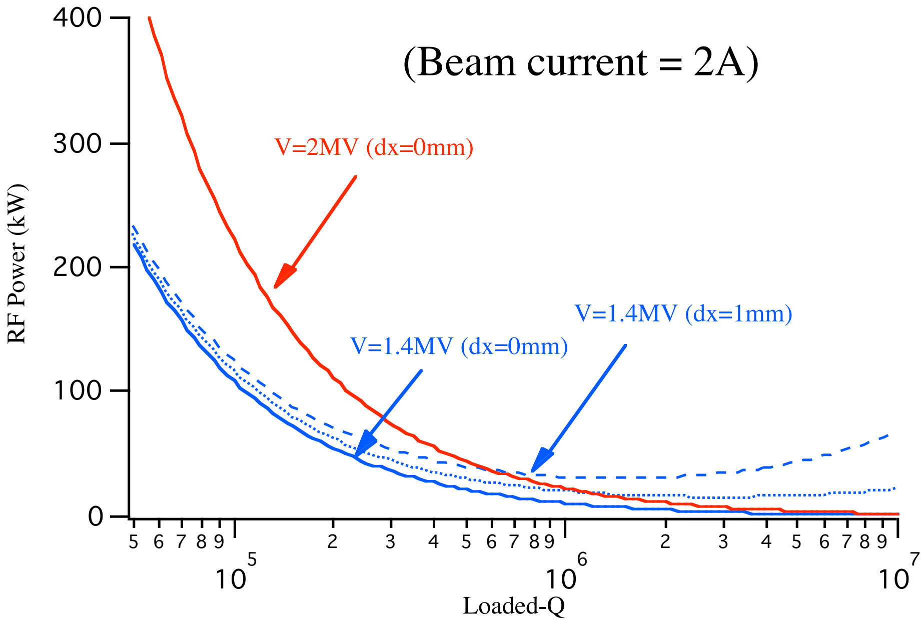
Two RF high power stations have been built for crab cavities.

Two Toshiba klystrons

Power supply for the klystrons
Circulator and dummy load

Low-level RF control at D11-F for the HER crab cavity

RF power, orbit error and Loaded-Q



Required RF power as a function of Q_L.

Vc=1.4 MV for nominal operation, and
Vc=2 MV may be needed for cavity conditioning.
The case of an orbit error of 1mm is also shown.

- Beam-induced voltage:

$$V_{br} \propto Q_L I_b \Delta_x$$

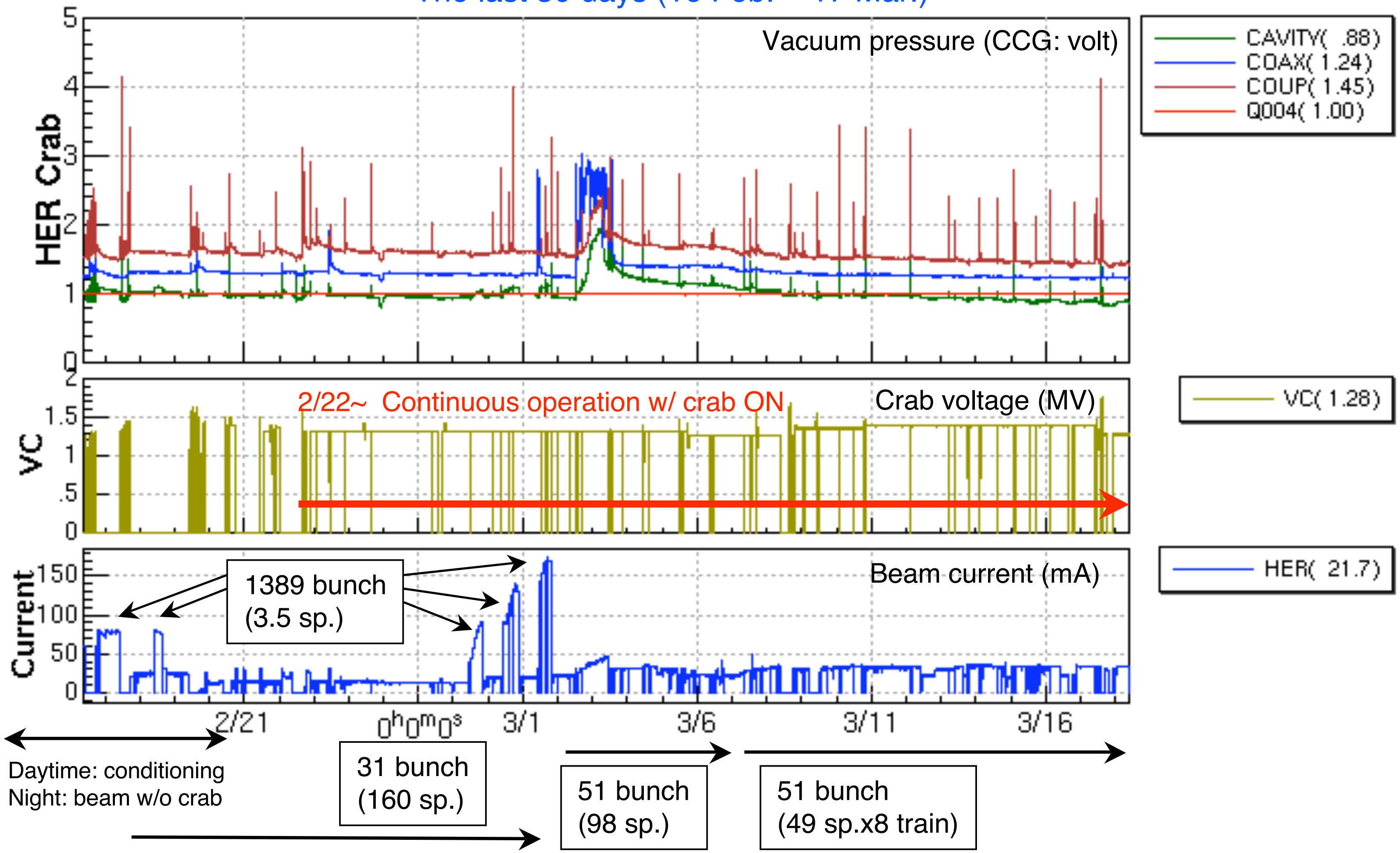
  - For example, for I_b=2A, Q_L=2E5 and Δ_x=1mm, V_{br} is 0.2 MV.
  - For stable operation, lower Q_L is desired and a large orbit error should be avoided.
  - Low Q_L increases RF power.
- Q_L=1~3 x10^5 is a good choice.
  - RF power of 200 kW is enough for conditioning the cavity up to 2 MV.
  - Not too sensitive to orbit change: tolerable to an orbit error of 0.5mm.
  - The beam orbit will be kept stable by an orbit feedback
- Measured at horizontal tests
  - Q_L = 1.34 x 10^5 (HER)
  - Q_L = 2.07 x 10^5 (LER)

Beam commissioning with crab cavity

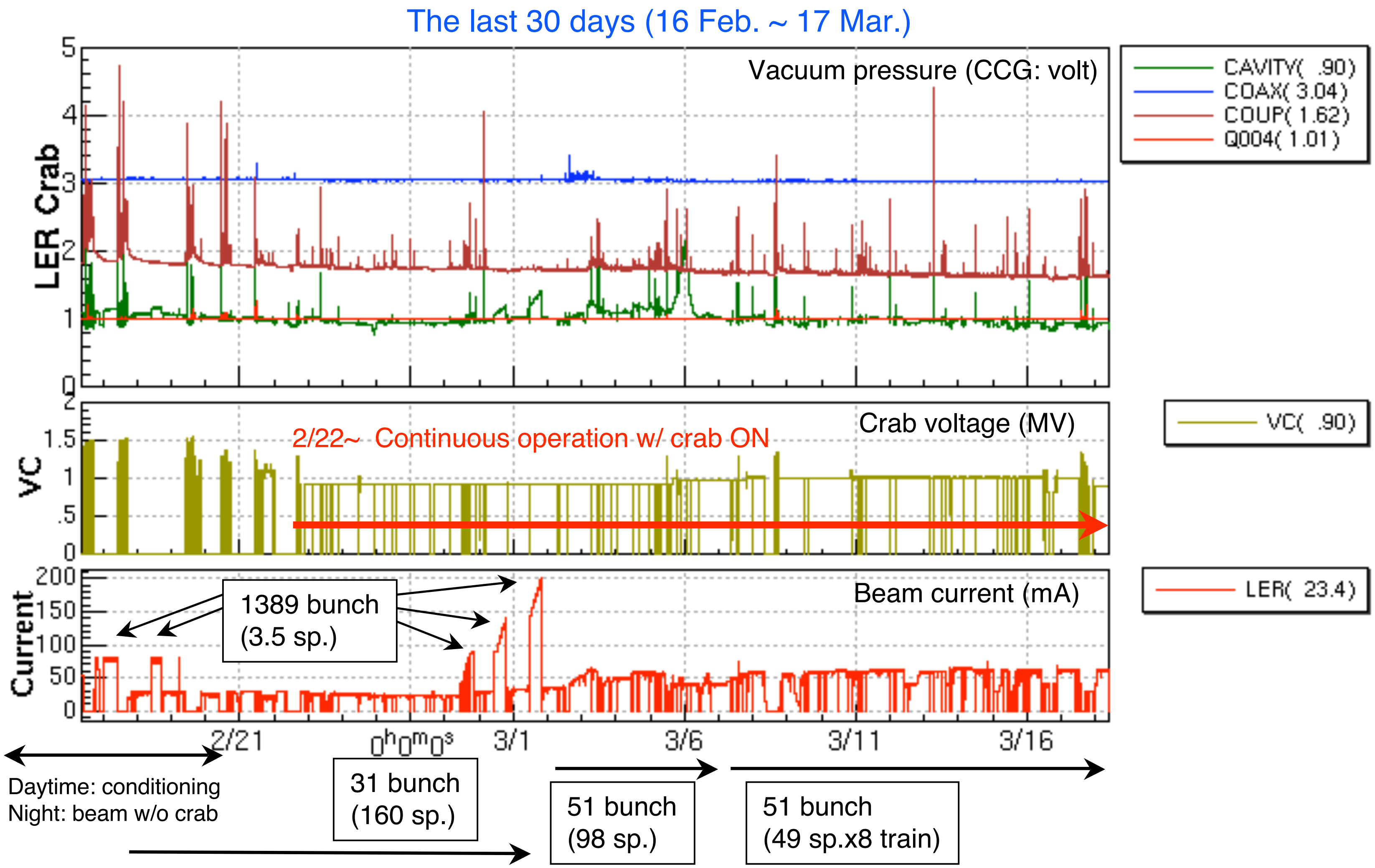
- Feb. 13~18
  - Daytime: conditioning crab cavities continued.
  - Night time: beam operation with crab cavities detuned.
    - Orbit center checked. Local bump made at crab cavities.
- First beam with crab ON (Feb. 19).
  - Crab phase was adjusted by observing beam orbit change.
  - Crab voltage was calibrated from beam orbit change.
  - Tilt of bunches was observed by a streak camera.
- First crab collision (Feb. 21).
- Continuous operation with crab ON (Feb. 22~).
  - Collision tuning continues
  - Beam current increase with various fill patterns

Operation summary of crab cavity (HER)

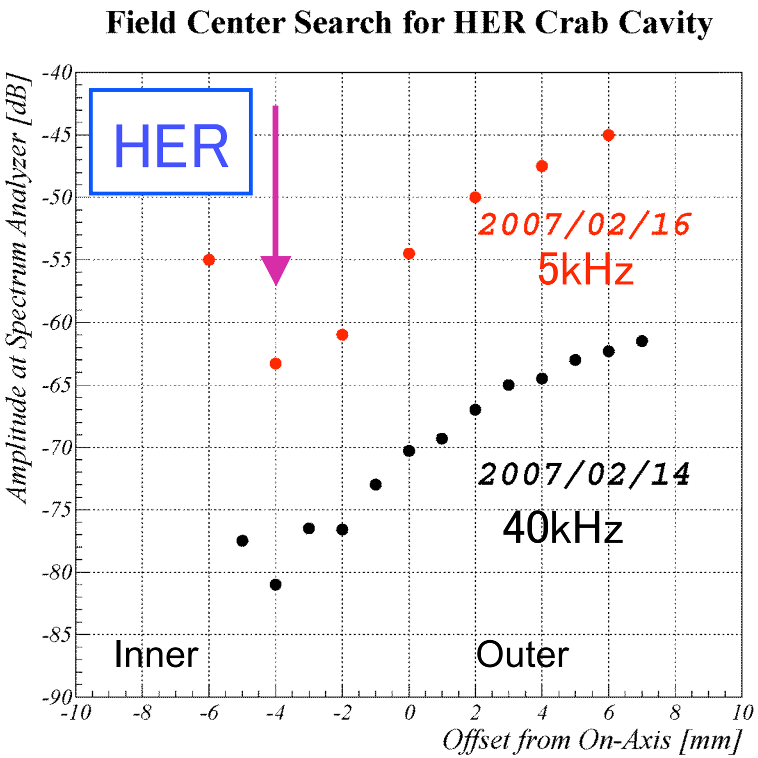
The last 30 days (16 Feb. ~ 17 Mar.)

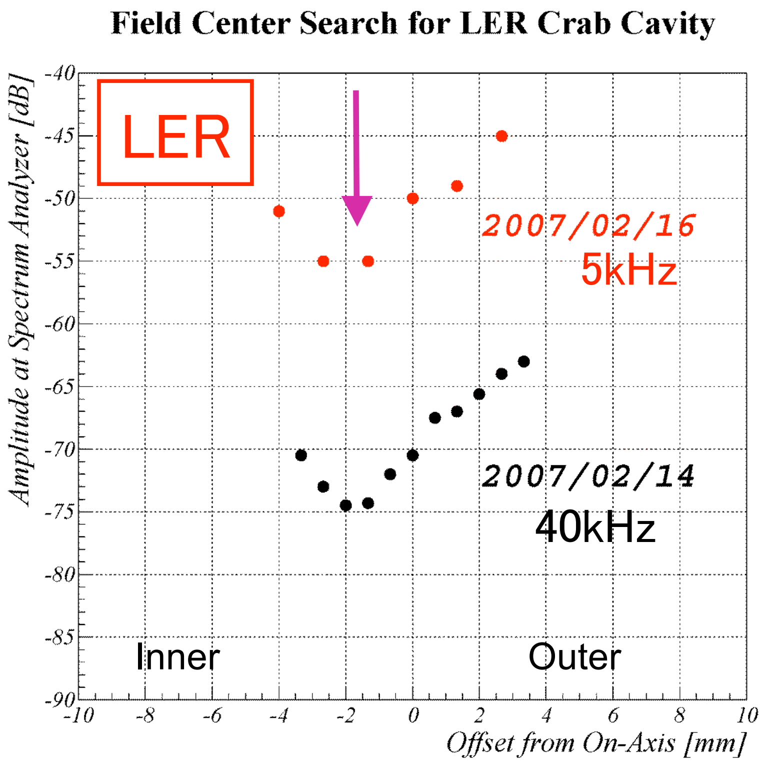


Operation summary of crab cavity (LER)



Searching Field Center in Crab Cavity





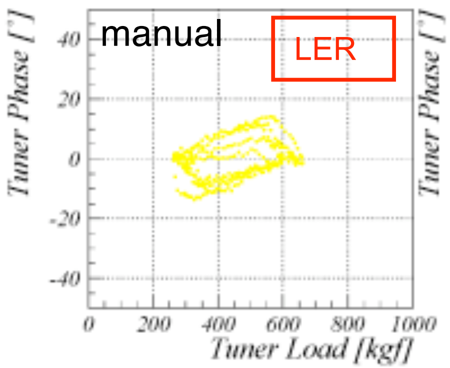
- Field center was searched by measuring the crabbing mode amplitude excited by a beam with the crab cavity detuned. Two measurements with different detuning frequencies agreed to each other.
- A local bump orbit was set to make the beam aligned on the field center.

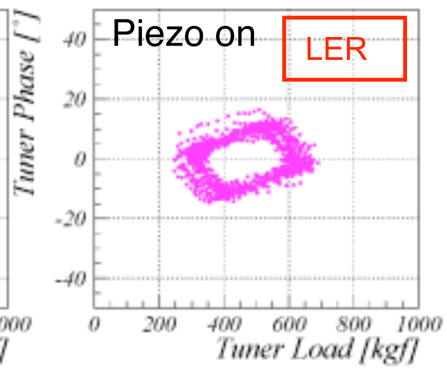
Adjustment of crab voltage and phase

- Calibration of crab voltage
  - Usual calibration method by using external Q values of pickup port measured at vertical test could not be applied, since the coupling was changed after the vertical test.
  - Crab voltage was adjusted from klystron output power and loaded-Q value of cavities, taking account of power loss from klystron to cavity of 12% (HER) and 5% (LER).
- Comparison with beam measurement
  - Kick voltage was calculated from beam orbit by changing the crab phase.
  - The RF calibration and beam measurement are in very good agreement:
    - HER 1.0 MV (RF) ⇔ 0.992 MV (beam)
    - LER 1.0 MV (RF) ⇔ 0.987 MV (beam)
- Phase of crab RF stations
  - Adjusted so as to minimize the COD generated by the crab kick.
  - Fine adjustment is done anytime, if needed.
  - Phase stability will be discussed later.

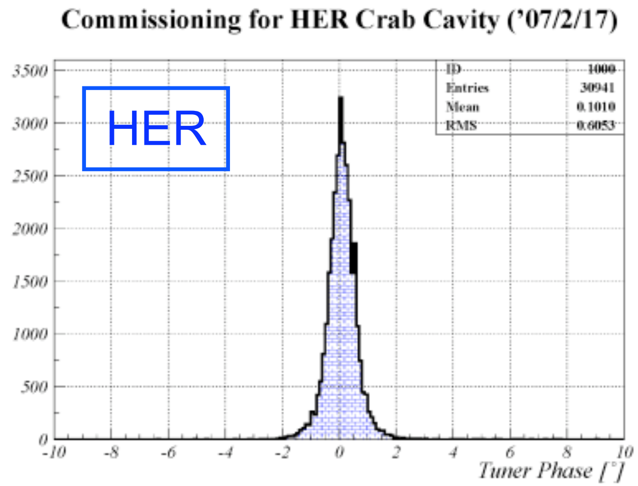
LER tuning mechanism problem

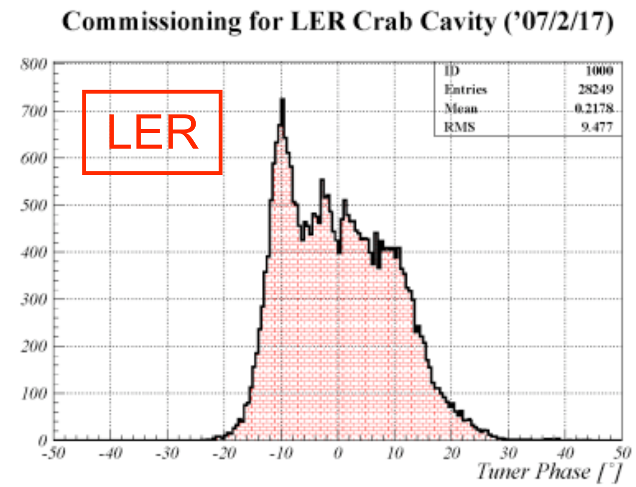
- Problem of LER frequency tuner:
  - Suffers from something like mechanical backlash. This results in a large fluctuation of tuner phase, even tuning feedback system is working.
  - Although some efforts were effective to reduce it, we still have a tuning error of about ±15 degree.
- Consequences:
  - Cavity phase is successfully stabilized to a required level by a phase lock loop (next two slides).
  - Cavity input power inevitably fluctuates to keep the cavity voltage constant.
  - Some of the LER trips seem associated with this fluctuation (discussed later).



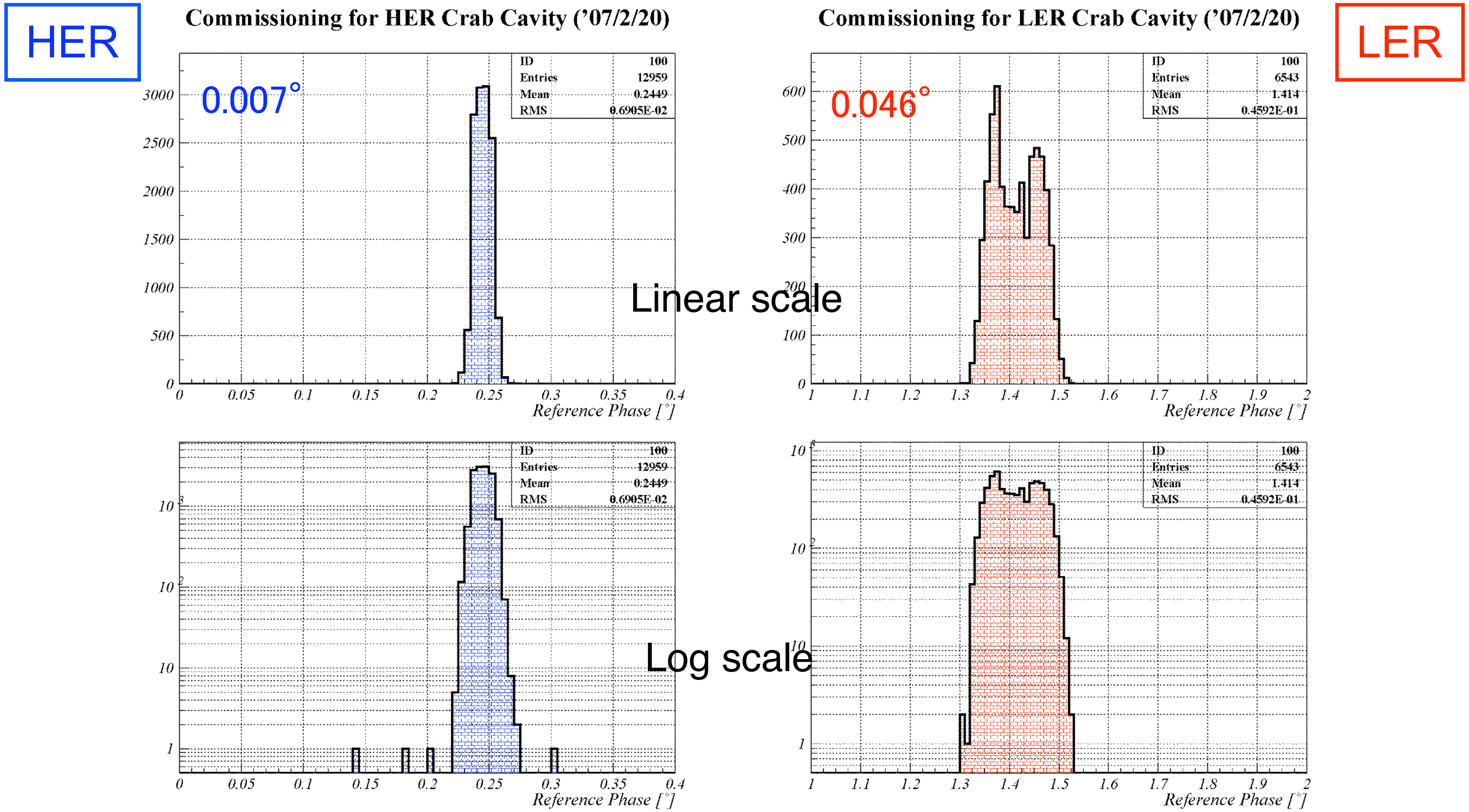


Distribution of tuner phase for Vc > 0.3 MV





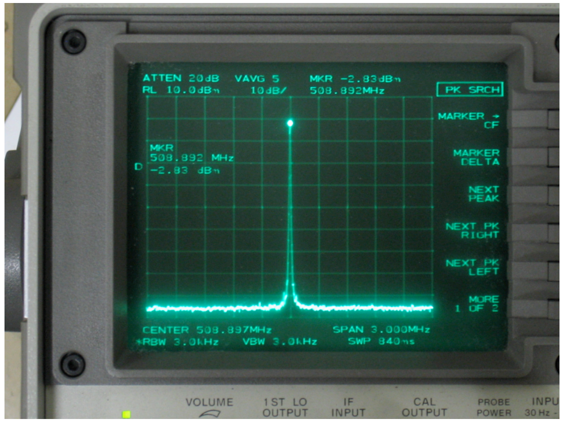
Phase stability (histogram of phase detector signal)



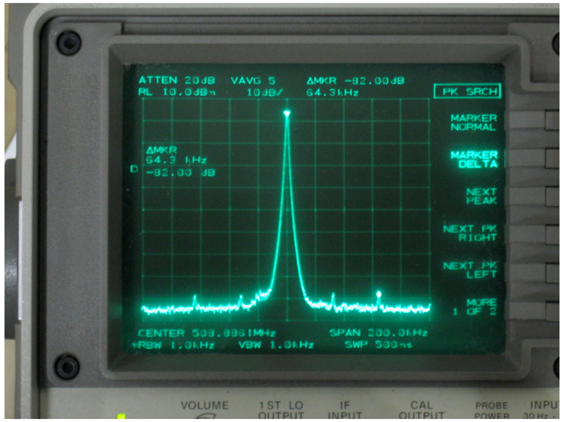
Distribution of cavity phase (cavity feedback loops on)

Phase stability (cavity pick up signal)

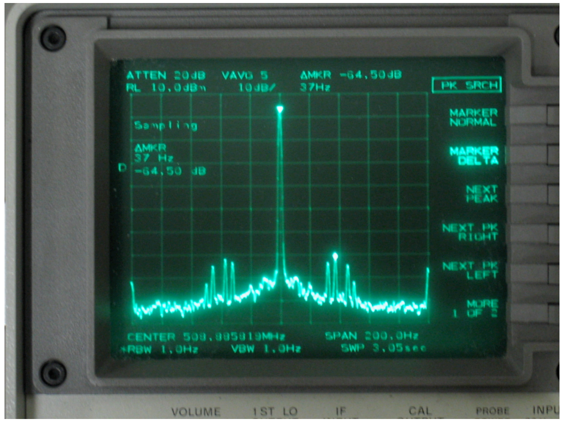
LER



Span 3MHz
No significant sidebands seen.



Span 200 kHz
Sideband peaks at 32kHz, 64kHz.
Phase error < ± 0.01 deg (fast)



Span 200 Hz
Sideband peaks
at 32, 37, 46, 50, 100 Hz.
Phase error < ± 0.07 deg (slow)

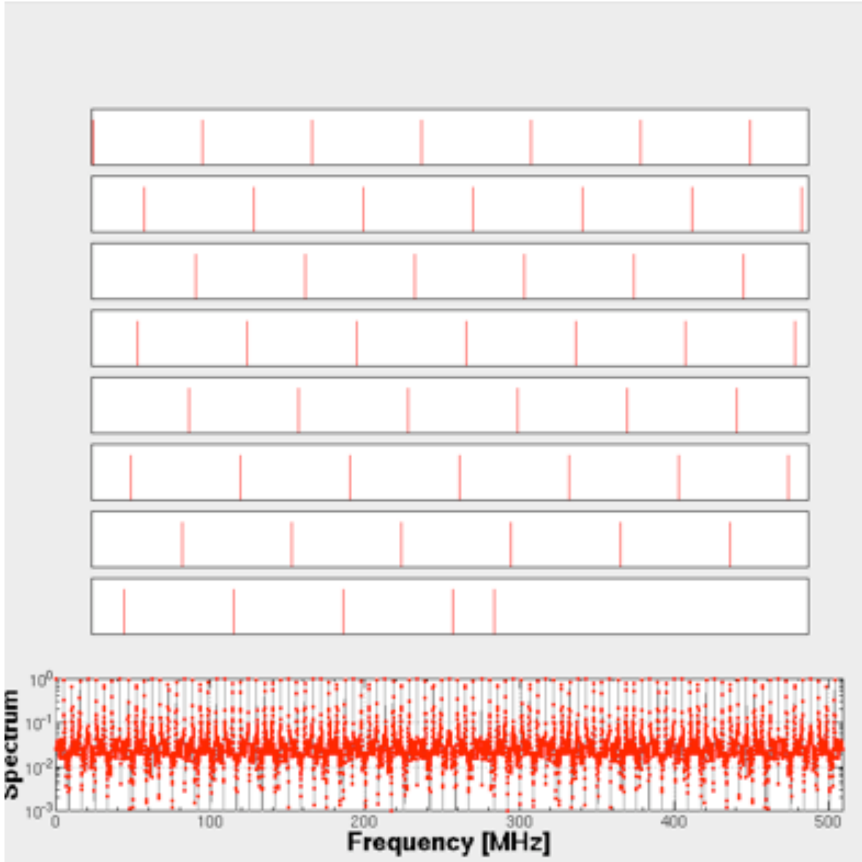
According to b-b simulation by Ohmi-san, allowed phase error for N-turn correlation is $0.1\times\sqrt{N}$ (degree).

- Spectrum of pick up signal is consistent with phase detector data.
- The measured phase error is much smaller than the allowed values given by beam-beam simulation.

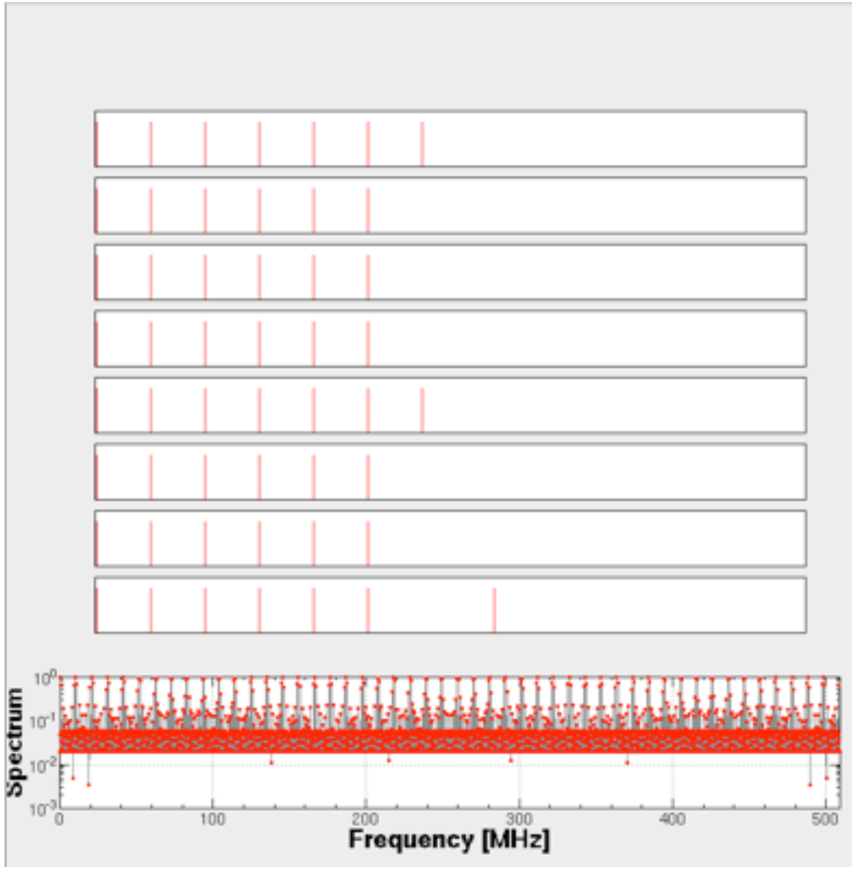
Bunch fill pattern

- Target fill pattern for the coming medium beam current operation is decided by commissioning group as:
  - Number of bunches is 201.
  - Bucket spacing is 24 and 25 (repeated for every 49 buckets).
    - 49 bucket spacing enables us to use 2 bunch injection scheme.
  - Total beam current will be 300mA (LER) and 200mA (HER).
- To smoothly reach this target, we proceed small current operation as:
  - Changed to 51 bunches (98 bucket sp. x 1 train) from the initial 31 bunches (160 bucket sp.) operation.
  - Next changed to 51 bunches (49 bucket sp. x 8 trains).
  - Maybe one months later we will gradually increase the number of bunches until 101 (49 bucket sp. x 1 train).
  - Then will gradually increase the number of bunches until 201 (24/25 bucket sp. x 1 train).
- This approach has advantage from the view point of HOM resonance.
  - No new major HOM resonance appear at each step.
- In parallel, we have also checked performance with high total beam current by storing 1389 bunches (3.5 bucket sp.) up to 200mA.

51 bunches, 98 bucket spacing



51 bunches, 49 bucket spacing x 8 trains

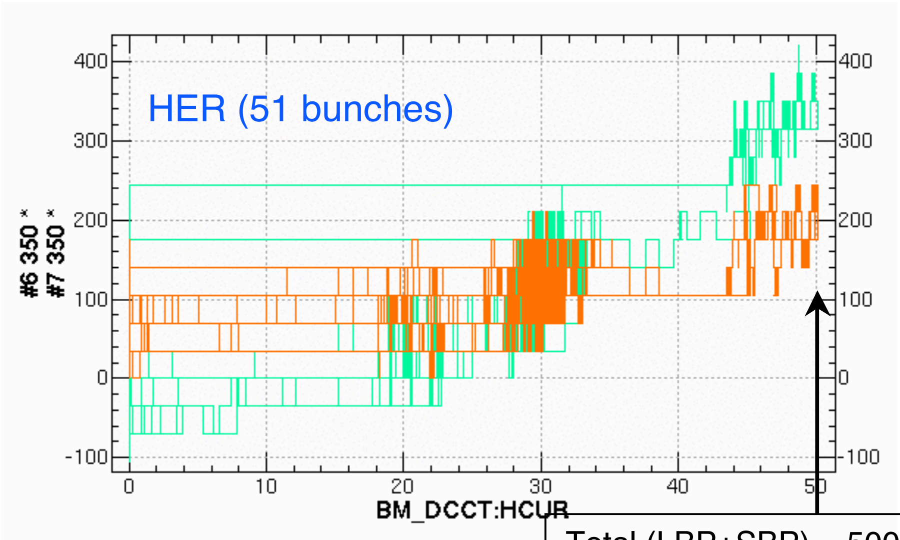


Crab voltage and beam current

		HER	LER
Crab Voltage	Horizontal test	1.8 MV	1.93 MV
	Conditioning after installation	1.7 MV	1.6 MV →1.3 MV (2/20) →1.0 MV (3/17)
	Operating (most of time)	1.3 ~ 1.4 MV	0.9 ~ 1.0 MV
Beam Current	1389 bunches (3.5 bucket sp.)	174 mA	200 mA
	31 bunches (160 bucket sp.)	32 mA	40 mA
	51 bunches (98 bucket sp.)	47 mA	65 mA
	51 bunches (49 bucket sp. x8 trains)	50 mA	75 mA

Measured HOM power and calculation

Measured power from temperature rise of HOM damper cooling water

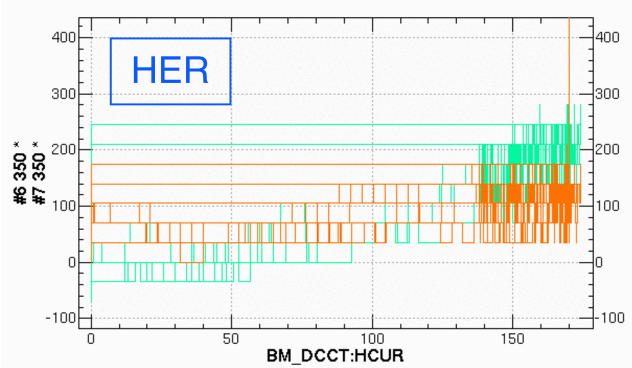


Total (LBP+SBP) ~ 500 W @50mA

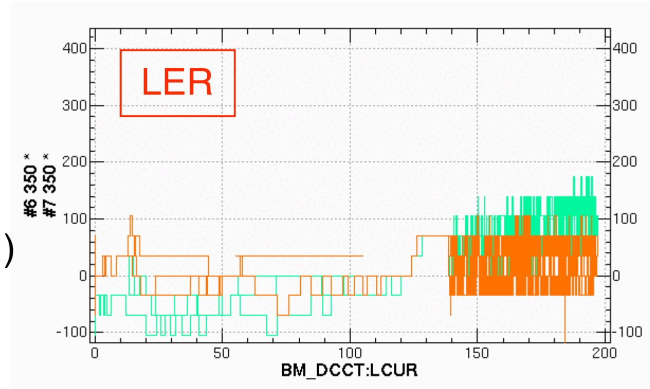
- Loss factor @σ_z=6mm (Y. Morita)
  - Cavity+ taper = 0.85 V/pC
  - Damper @LBP = 0.25 V/pC
  - Total = 1.1 V/pC
- Calculated HOM power from Loss factor is
  - $P_{hom} = k_{loss} \times T_0 \times I^2/N_b$
  - k_{loss} =1.1 V/pC, T=10μs
  - I=50 mA, N_b=51 → k_{loss}= 540 W

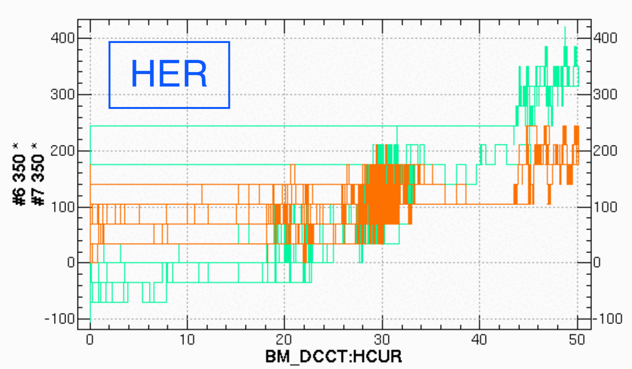
- Measured power and calculation are in fairly good agreement, considering poor accuracy of temperature measurement for small beam current.
- Further study will be done with higher beam current.

HOM power for various bunch fill patterns

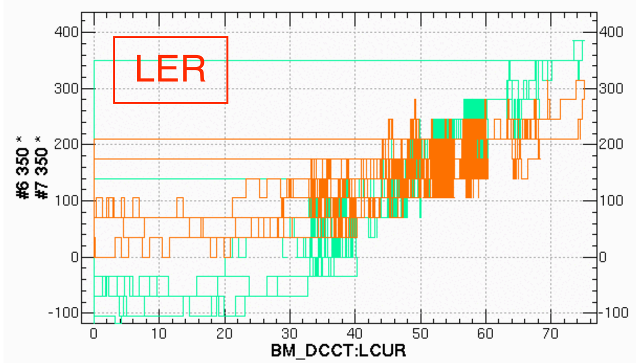


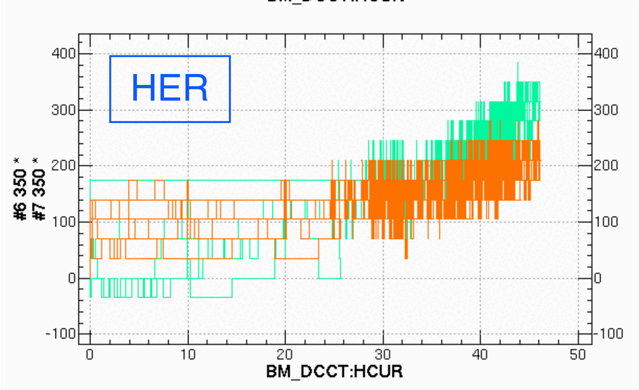
1389 bunches
(3.5 bucket sp.)



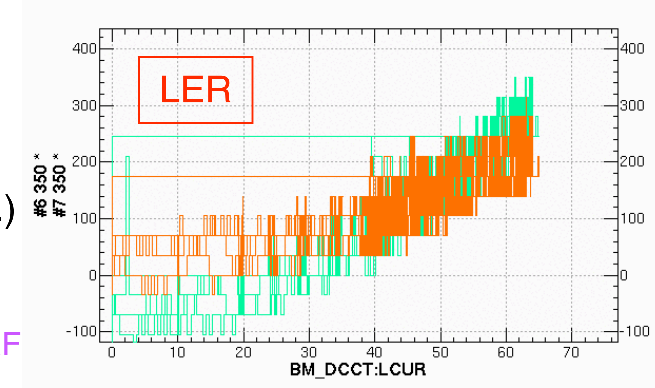


51 bunches
(49 bucket sp.
x 8 trains)

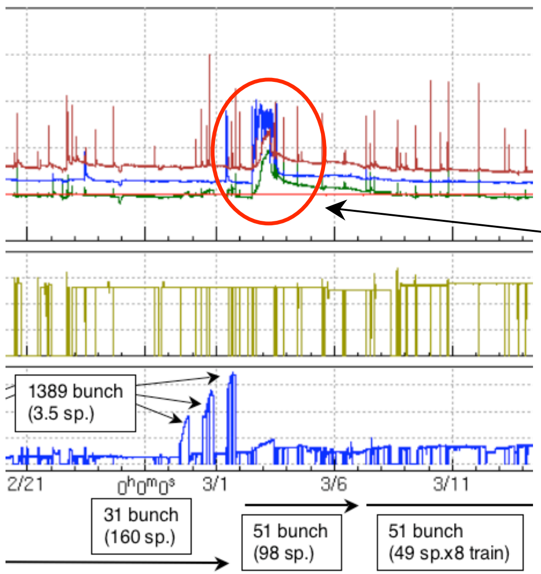




51 bunches
(98 bucket sp.)



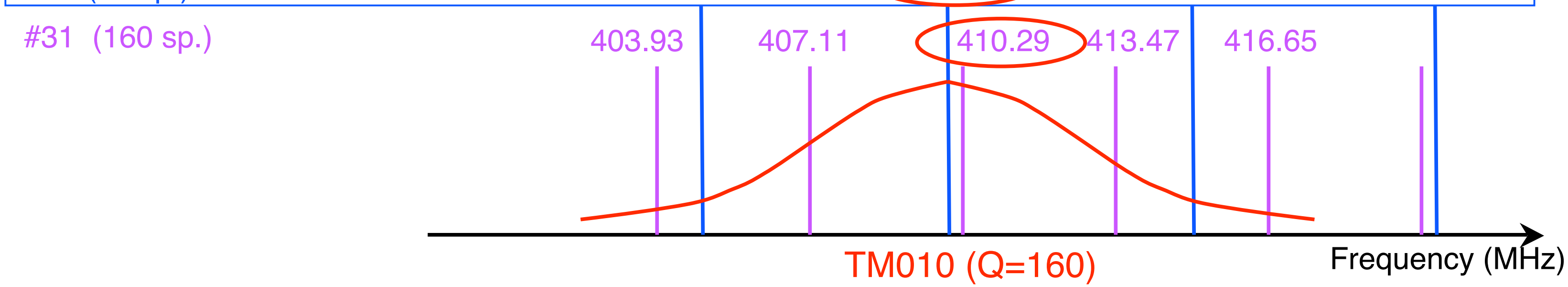
Lower frequency mode (TM010)



- TM010 (accelerating mode) is heavily damped by the coaxial beam pipe. Nevertheless, it can be resonantly built-up when hit by one of beam spectrum.
- We observed vacuum pressure rise at coaxial beam pipe for a bucket spacing of 160 or 98, but no significant pressure rise for 49 spacing.
- The resonance is avoided for high beam current operation with a bucket spacing of 49 or less.

bunches (bucket spacing)

#201 (24/25 sp.)	none	none	415.42	none
#101 (49 sp.), also #51 (49 sp. 8 train)	405.03	none	415.42	none
#51 (98 sp.)	405.03	410.23	415.42	420.61



Cavity trips during beam operation

- The number in the table shows beam aborts associated with crab cavity trips.
  - In most cases beam is automatically aborted by interlocks.
  - In other cases the beam survives. But the beam is manually aborted for safety before recovering the crab cavity.
  - Down during the recovery process after the event of abort is not included. Sometimes we need conditioning to recover it.
- The average trip rate is 1.7/day for HER and 3.4/day for LER.
  - In most cases the trip is associated with vacuum pressure rise and/or quench. It seems that the cavity has accumulated a large amount of gas on the surface during the initial operation.
- So far the trip frequency is acceptable to beam operation.
  - Warming up the cavities to 80 K may further reduce the trip frequency.

Statistics of crab cavity trips for the last 2 weeks (Mar. 4-17)

Date	HER	LER
March 4	2	4
5	2	6
6	1	2
7	3	2
8	1	2
9	1	2
10	4	1
11	0	4
12	1	2
13	2	4
14	2	2
15	2	6
16	2	6
17	1	5
Total in 14 days	24	48
Trips / day	1.7	3.4

Problems of LER cavity and cures to be taken

- Degradation of crab voltage
  - Maximum voltage of LER cavity has degraded from 1.6 to 1.3MV, and recently to 1.0MV.
  - HER cavity once experienced similar degradation at the first horizontal test. It was drastically recovered after warming up to 80 K.
  - We hope that the LER performance will also be recovered by warming up to 80 K. It needs one and a half day shut down.
- More trips than HER cavity
  - The warming up to 80 K is also expected to reduce the trip rate.
- Less effective cooling of coaxial pipe
  - Due to longer return helium gas pipes the cooling of coaxial pipe is much less effective compared to HER cavity. It will be improved by making a bypass at the return pipes. This can be done while warming up cavities.
- Frequency tuner
  - As already discussed, tuning phase has a large fluctuation. Although the cavity field is sufficiently stabilized, it is desired to reduce it, if possible. Reinforce the support rod is planned while the warming up cavities.

Summary

- Two RF stations for crab cavities have been constructed in D11 in time for the crab cavity installation.
- The commissioning operation of crab RF system has been successfully performed.
- The crab cavities and RF system have been working satisfactory.
  - Cavities with peripheral components as well as RF system have been working, as expected.
  - The phase stability well meets the requirement from b-b simulation.
  - Trip frequency is acceptable.
- The cavity performance is excellent, except the degradation of LER cavity voltage.
  - In order to recover the LER cavity performance, warming up to 80 K is planned probably this week.
- We look forward to higher beam current operation.