Yoshiyuki MORITA
KEK

KEKB RF Cavity Commissioning and Operation

Introduction

Commissioning

Frequency tuner

Oscillation of high current crabbing beam

Trip rate

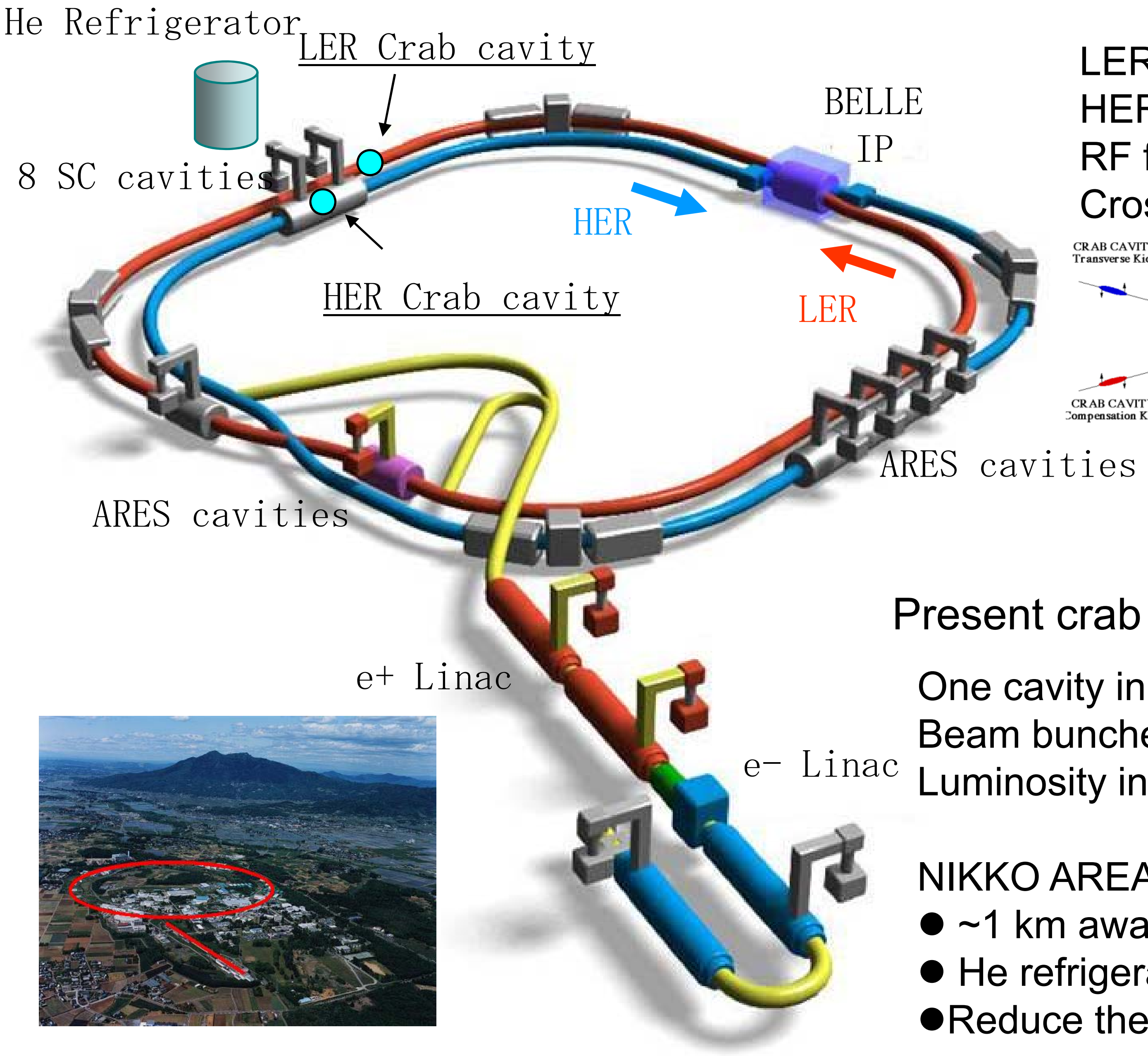
HOM dampers

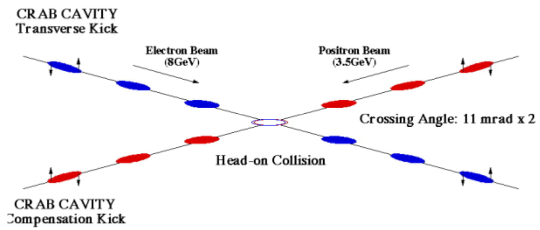
Beam-induced RF spectrum

Summary

KEKB

LER: e+ 3.5 GeV 1.7A
HER: e- 8.0 GeV 1.4A
RF freq.: 509 MHz
Cross. Angle: 22 mrad





Present crab crossing scheme

One cavity in one ring
Beam bunches wiggle in the ring
Luminosity increase (K. Ohmi)

NIKKO AREA

- ~1 km away from the IP
- He refrigerator (8 kW@4.4K)
- Reduce the construction costs

Crab Cavity Conceptual Design

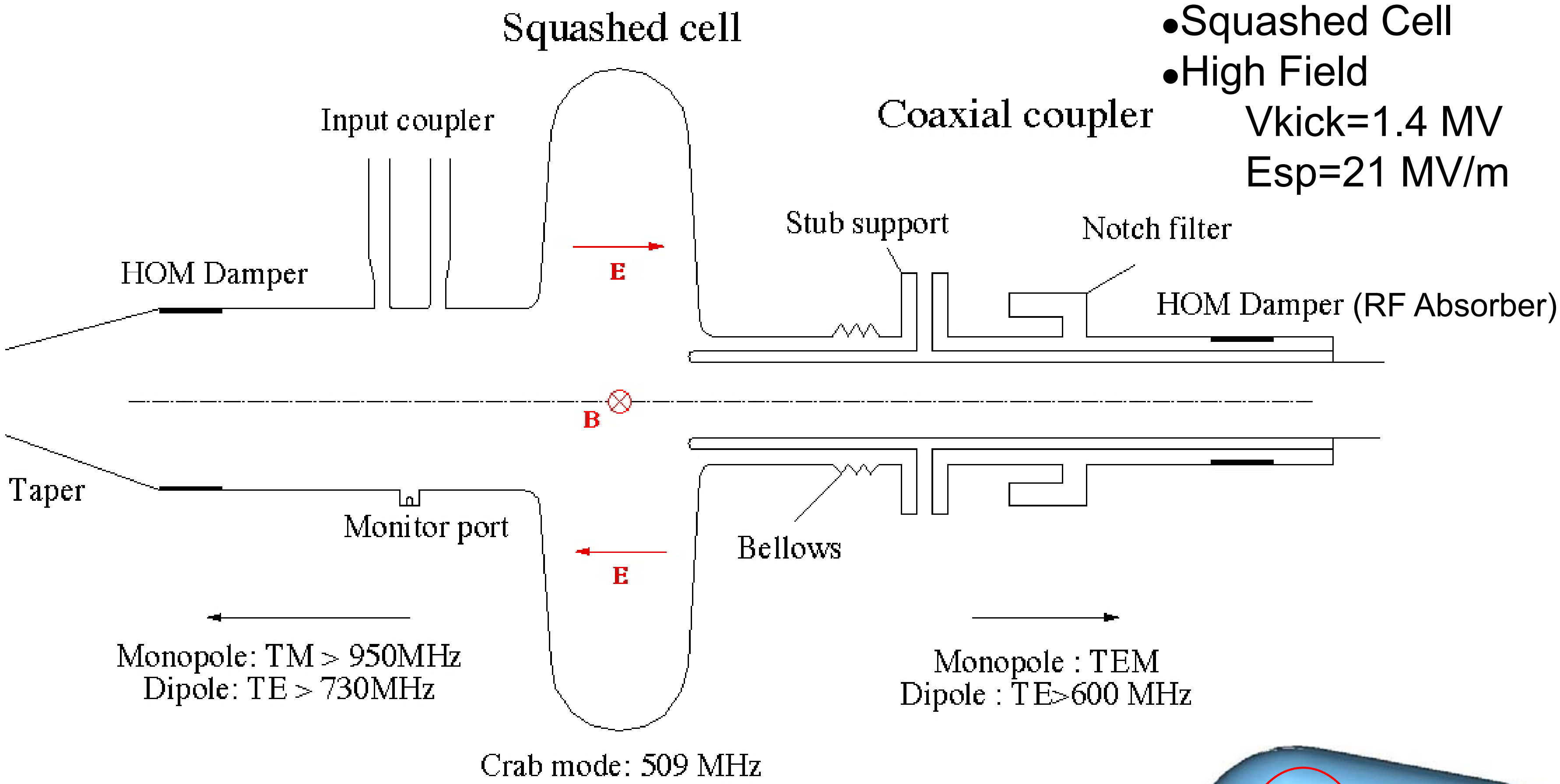
K. Akai

Unique characteristics

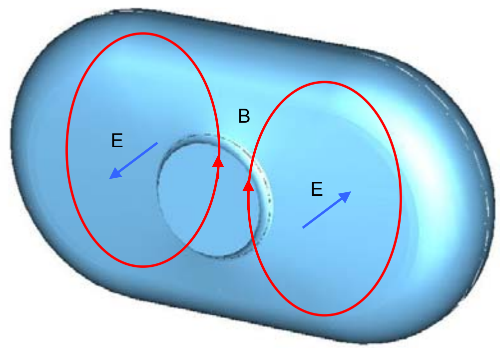
- Coaxial Coupler
- Squashed Cell
- High Field

  Vkick=1.4 MV

  Esp=21 MV/m



Crab Mode: TM110-like mode (high R/Q)
Coaxial coupler: LOM damping
Squashed cell: UWP > 600 MHz
Notch filter: TEM-coupled Crab mode rejection
Stub support: support for inner conductor



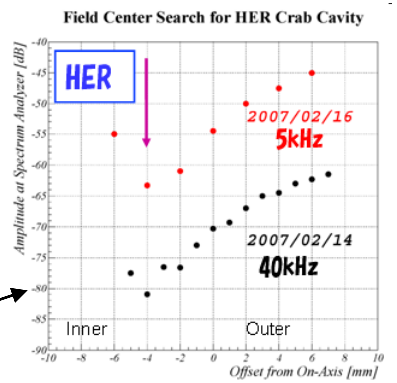
Commissioning and operation

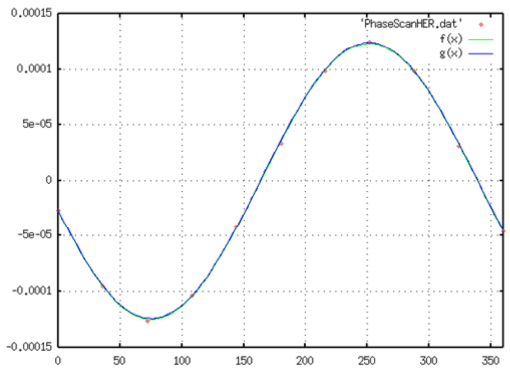
- Coupler aging at room temperature (up to 200 kW)
- Cool down (2 K/h for 1 week)
- Tuner adjustment
- Cavity conditioning
  - HER: >1.8 MV
  - LER: 1.5 -> 1.3 -> 1.1 MV

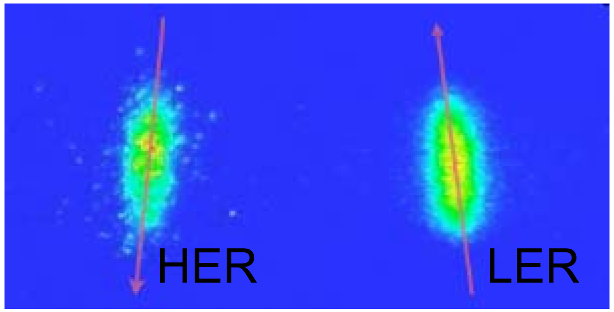
- Low beam current tuning for crab crossing
- Warm-up to 80 K and to room temperature
- High current operation and physics run

System adjustment

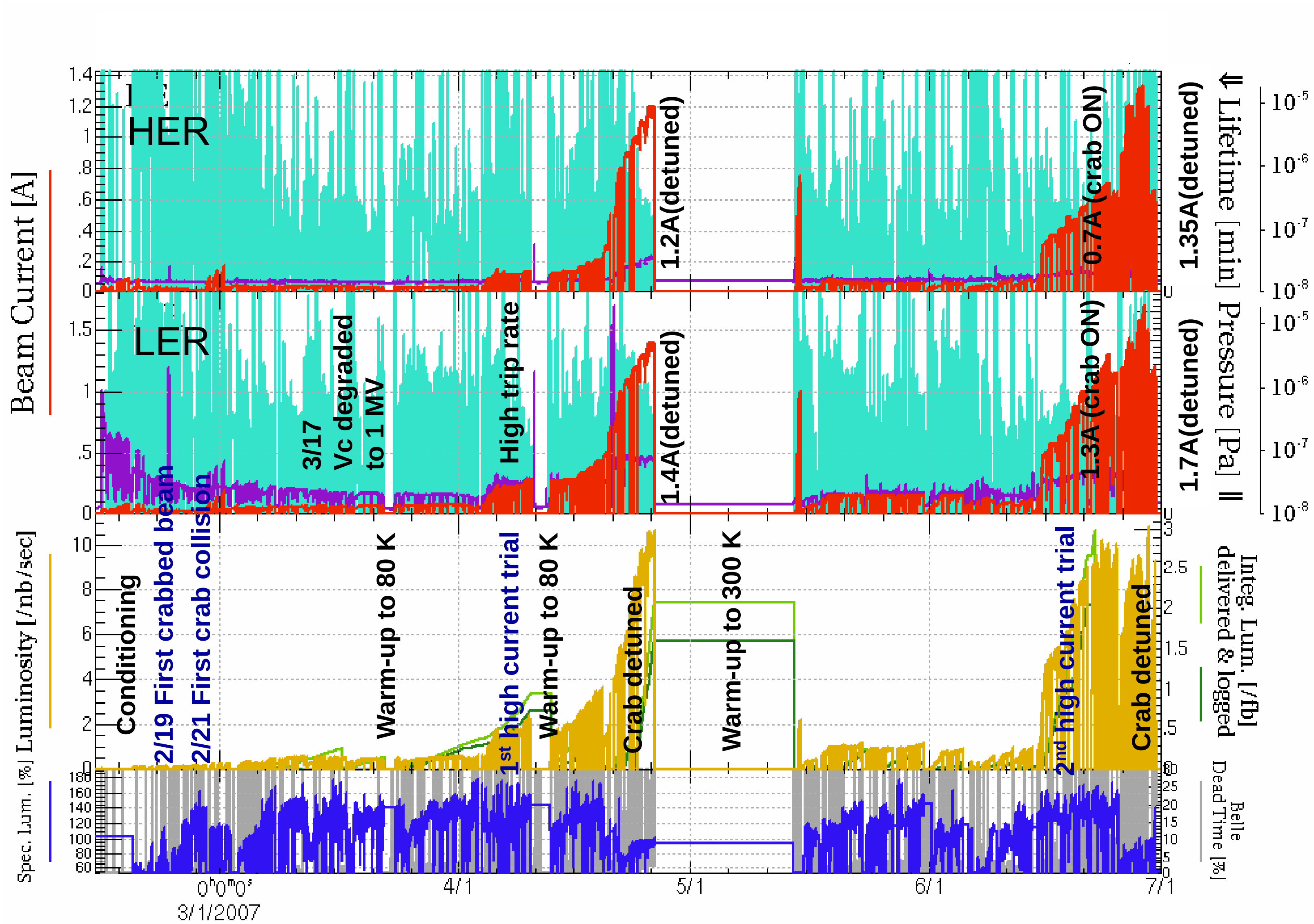
- Crabbing voltage
  - R/Q, Input RF power, Qext measured at Horizontal test
- Field center
  - Beam-induced crabbing amplitude with crab detuned
  - Local bump orbit
- Crabbing phase
  - Beam orbit difference (Crab ON/OFF)
  - Determine crabbing phase
  - Determine crabbing voltage
- Tilting angle of beam bunch
  - Streak camera (H. Ikeda)



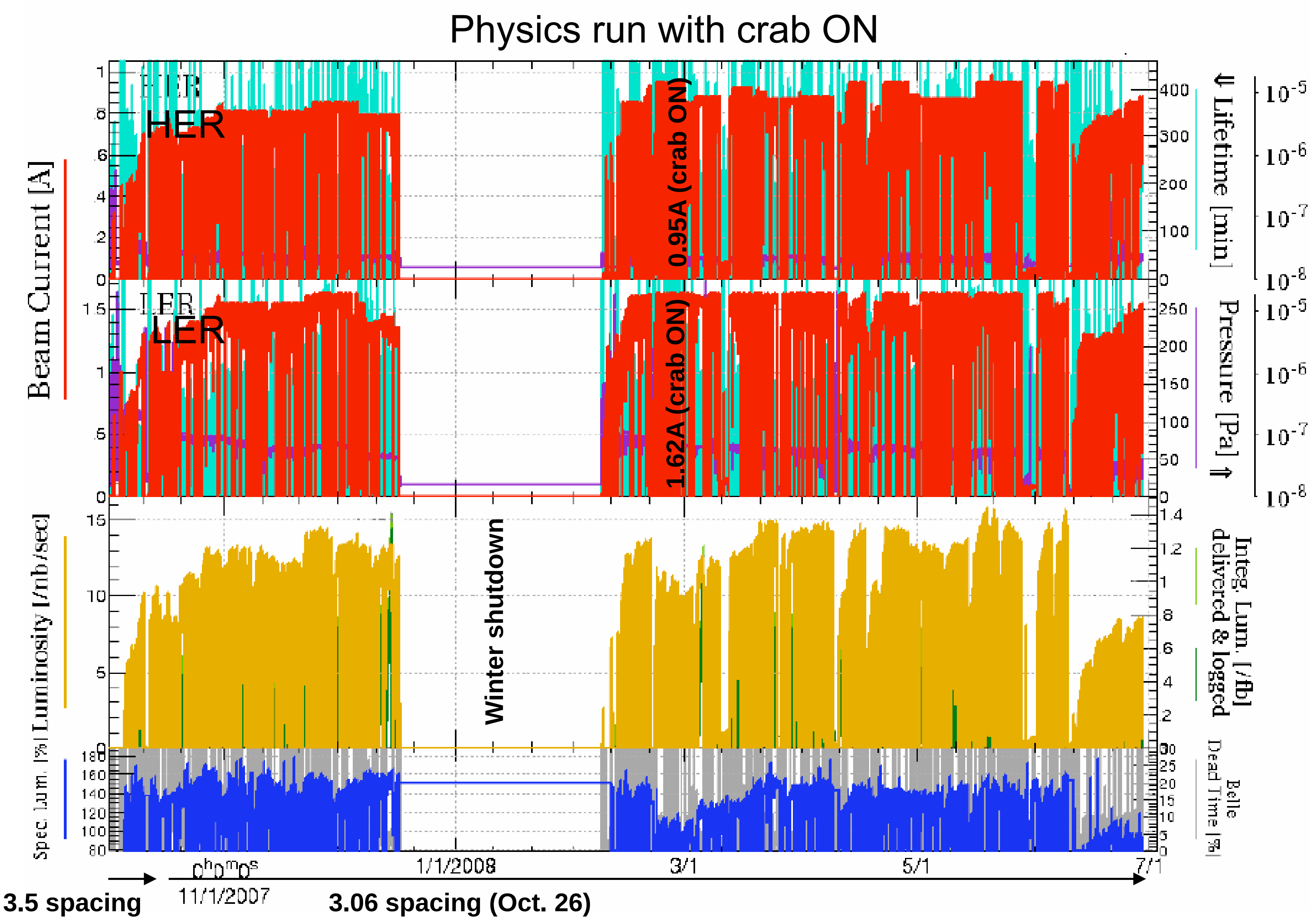




Overview of the crab commissioning (1st period)

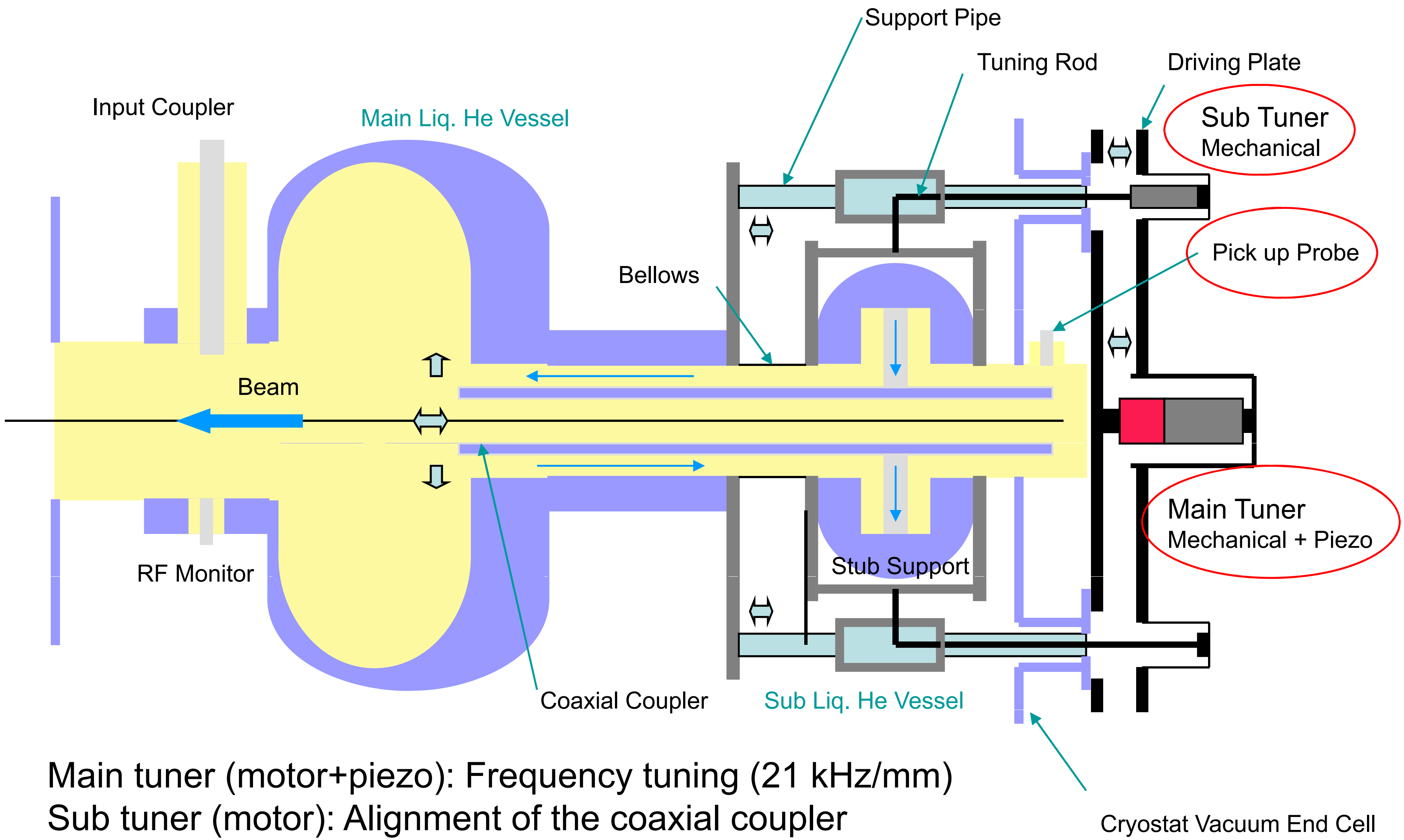


Overview of the crab commissioning (2^{nd} and 3^{rd} periods)



Frequency Tuner

K. Hosoyama

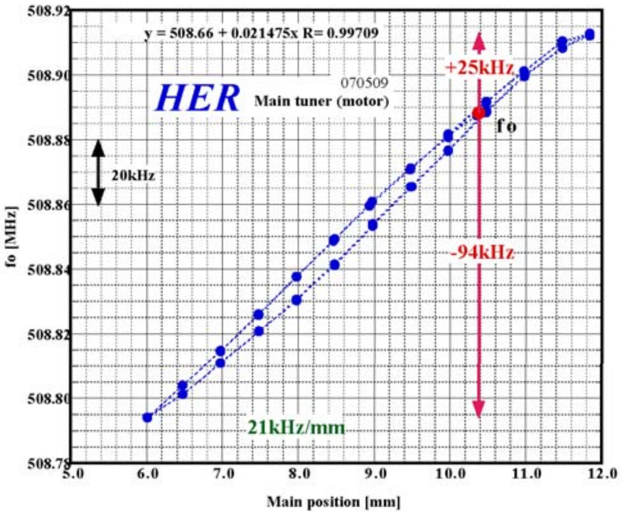


Main tuner (motor+piezo): Frequency tuning (21 kHz/mm)
Sub tuner (motor): Alignment of the coaxial coupler
Pick-up probe for monitoring crabbing-mode leakage

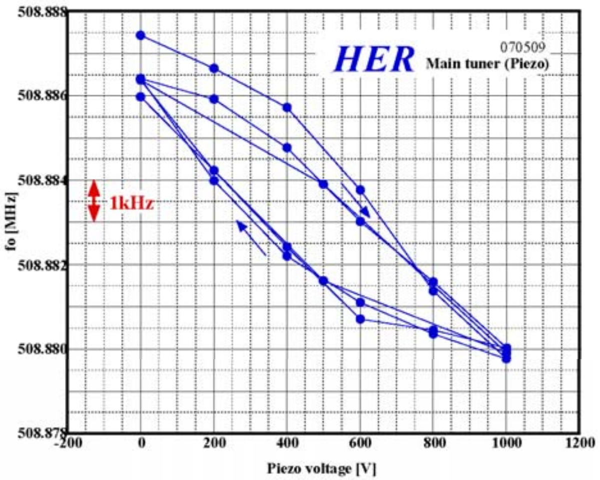
Tuner test

A. Kabe

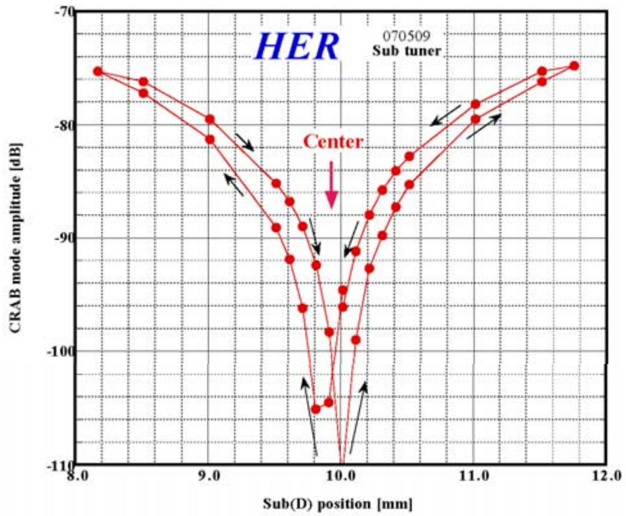
Tuning parameter: 21 kHz/mm
Main tuner (motor)

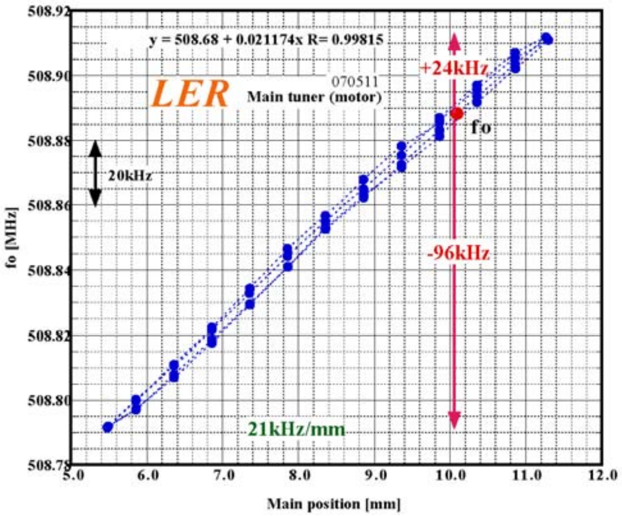


Fluctuation: +/-1 deg.
Main tuner (piezo)

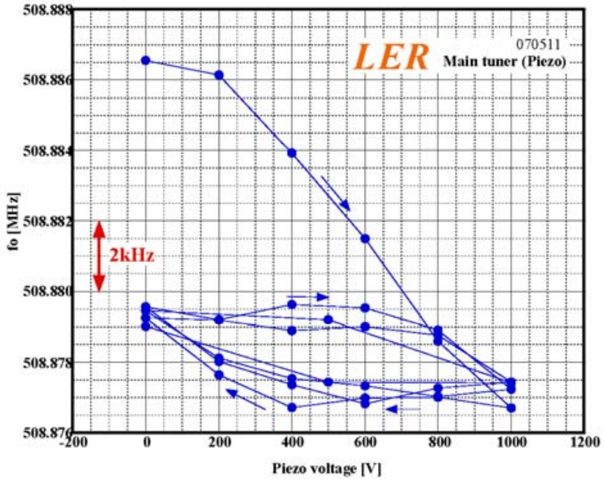


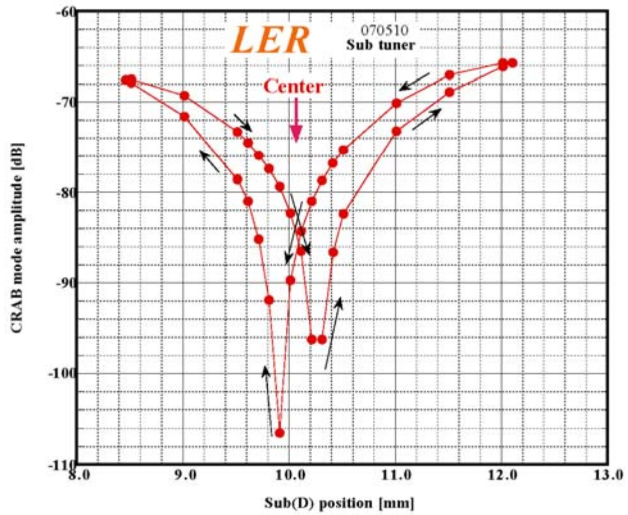
Alignment of the coax
Sub tuner (motor)





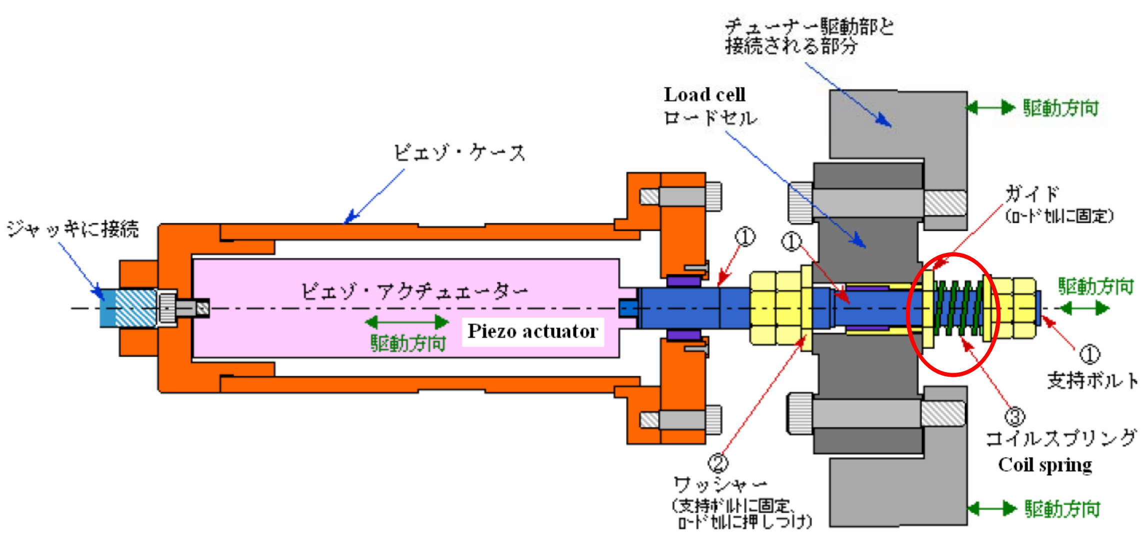
Fluctuation: +/-13 deg.

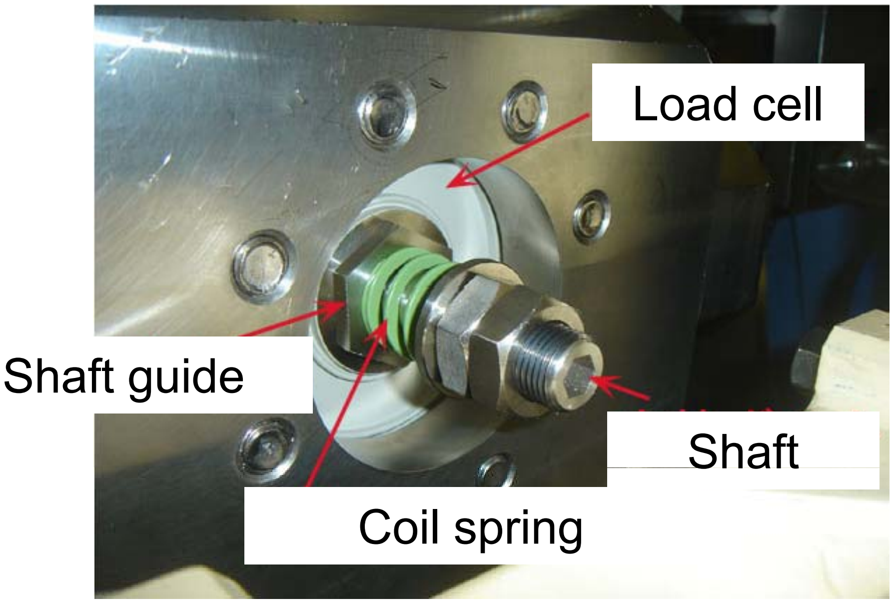




Tuning mechanism improvement

A. Kabe





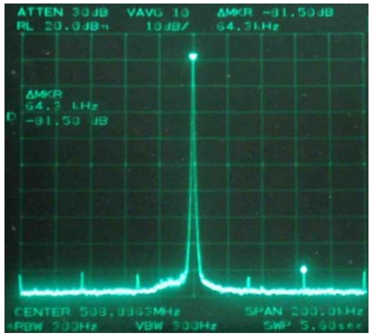
- Piezo actuators broke several times.
  - HER: 2 (Oct., 2007)
  - LER: 2 (June, 2007), 1(Oct, 2007)
- Coil spring added. (Jan., 2008)
  - No breakdown since then
- Pulling force is the cause ?

Phase stability

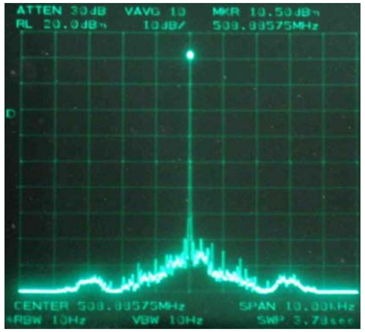
K. Akai

- 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.

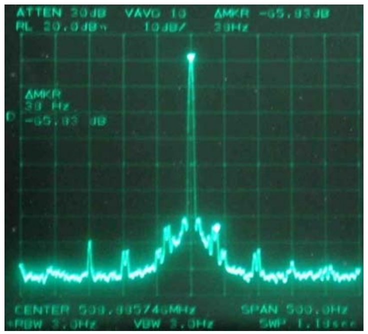
According to b-b simulation by Ohmi-san, allowed phase error for N-turn correlation is $0.1 \times \sqrt{N}$ (degree).



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

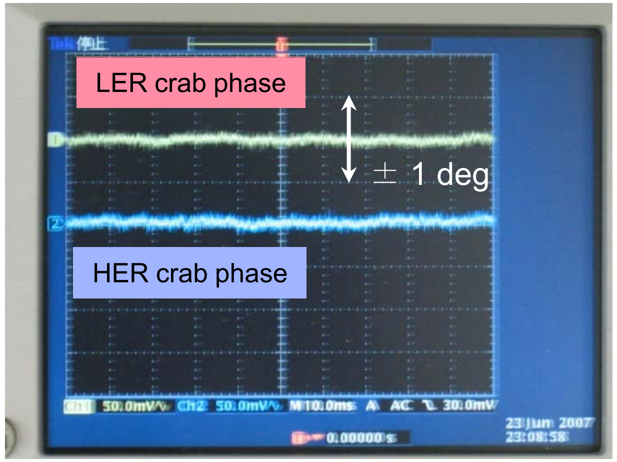


Span 10 kHz



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

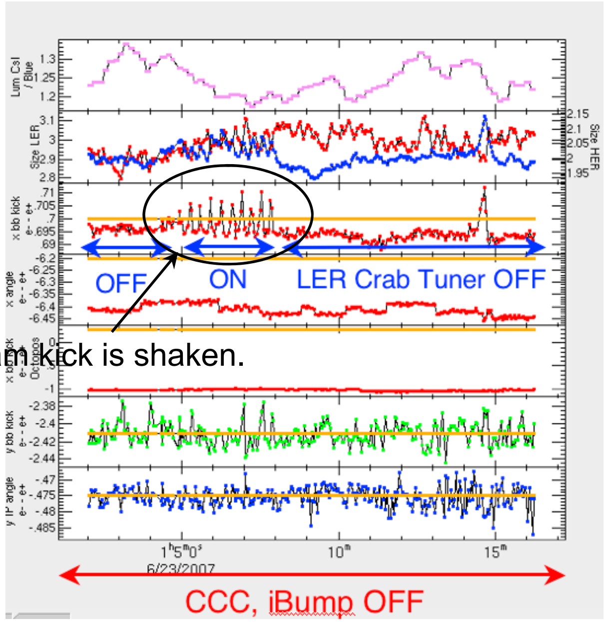
Spectrum around the crabbing mode measured at a pick up port of the LER crab cavity. Beam current was between 450 and 600 mA.

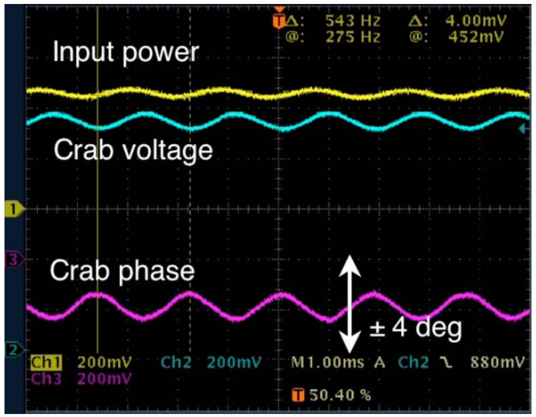


Phase detector signal. Beam current was 385mA (HER) and 600 mA (LER).

K. Akai

Oscillation of high-current crabbing beams

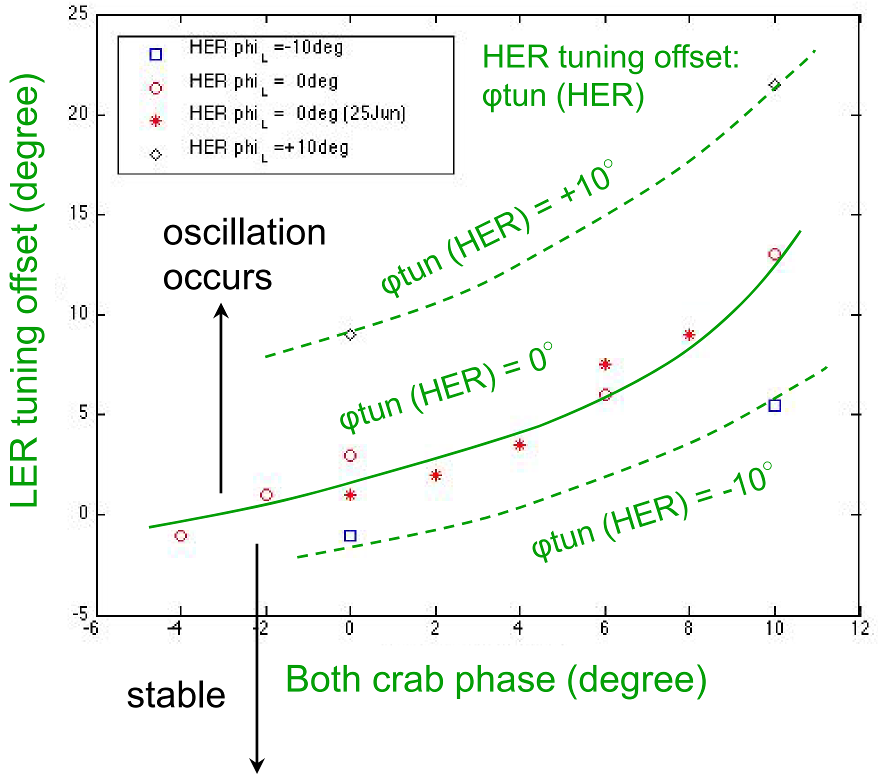




- A large-amplitude oscillation was observed in high-current crab-crossing operation in June.
  - It caused unstable collision, short beam life time and luminosity degradation.
  - Crab amplitude and phase were modulated at 540 Hz. Horizontal oscillation of beams was also observed at the same frequency.
  - 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.

K. Akai

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

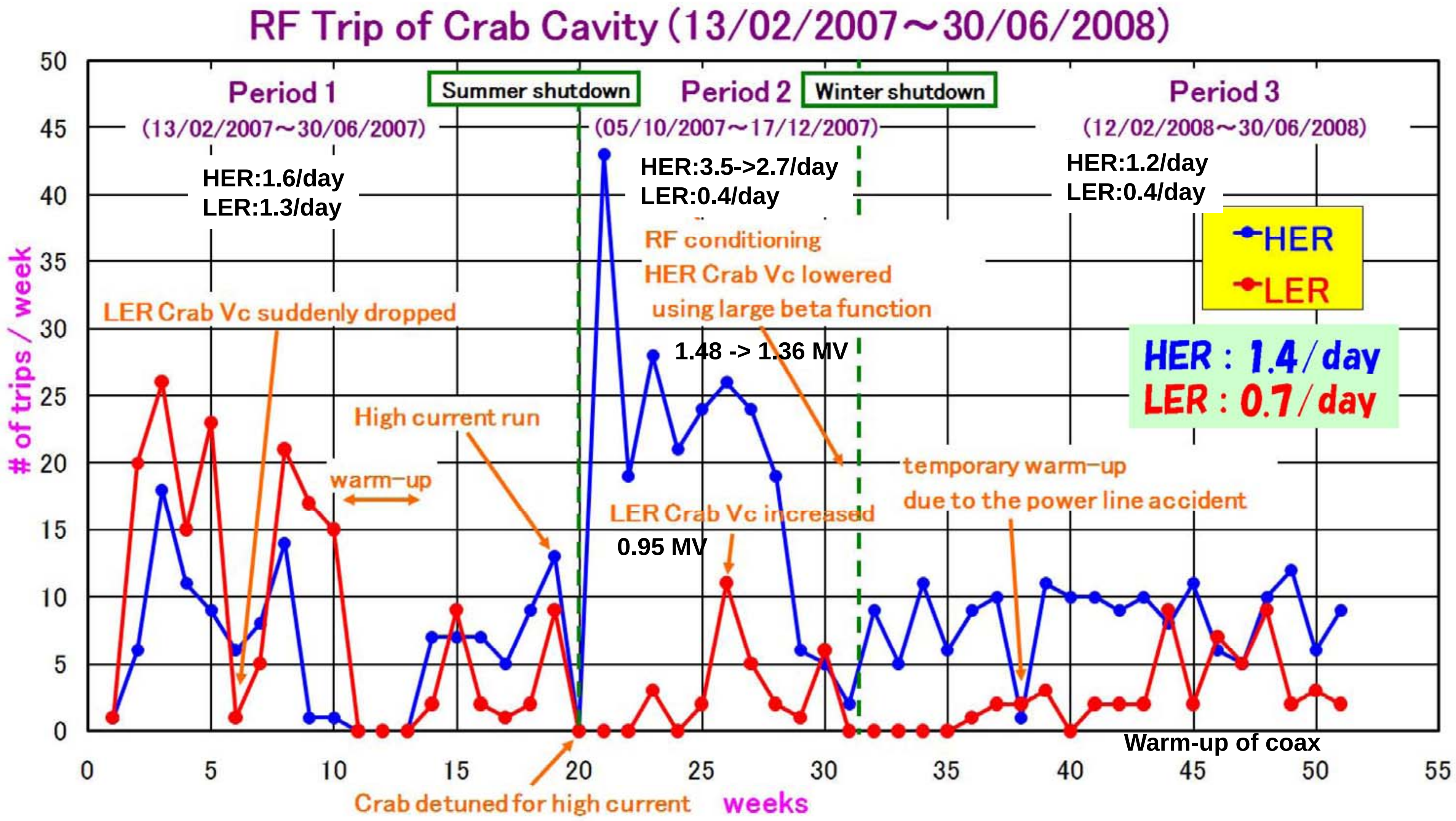
- The oscillation occurred only with high-current colliding beams: it never occurred with a single beam, even at a high current.
- Both beams oscillates coherently.
- The threshold for the oscillation is dependent on the crab phase and tuning phase (see left).

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.

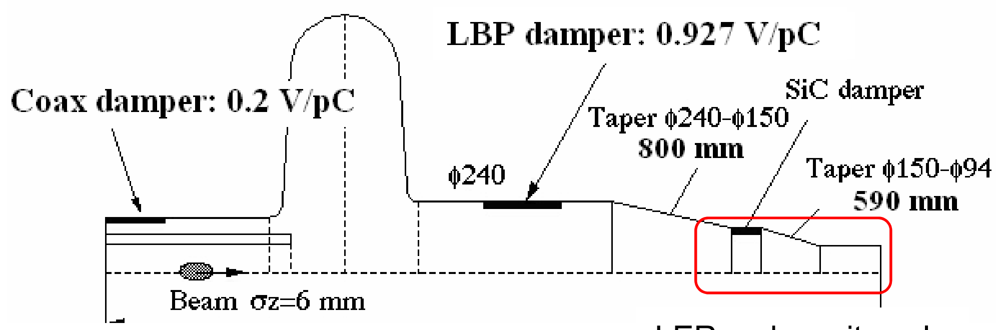
Kirk

Trip statistics

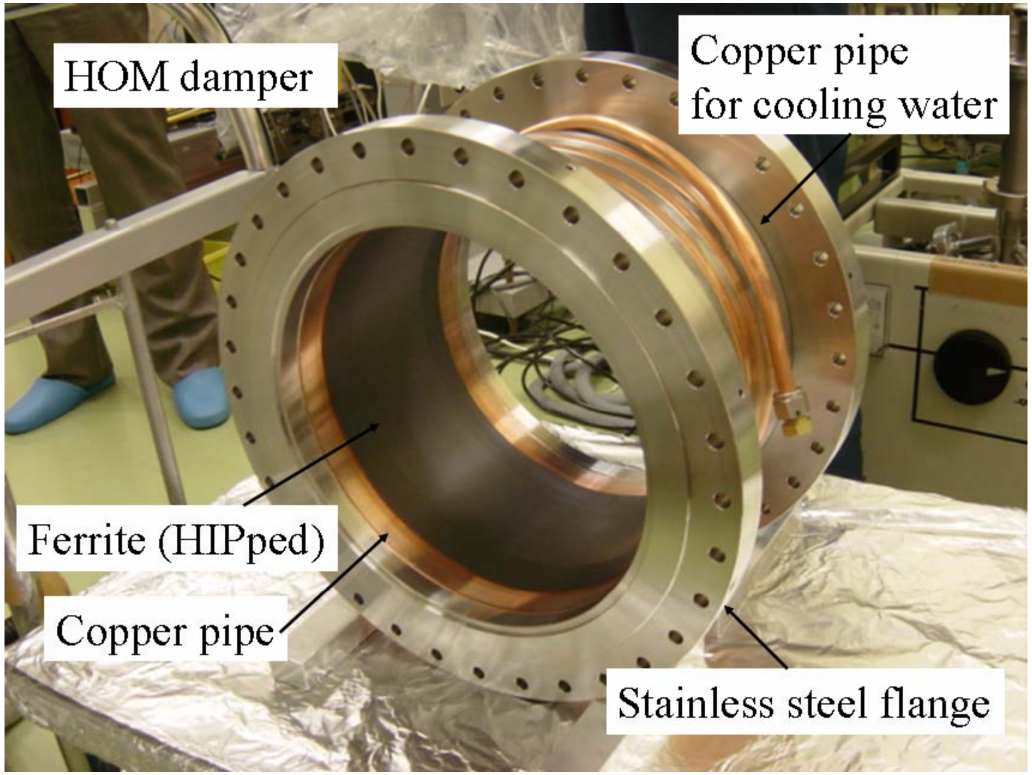


HOM dampers

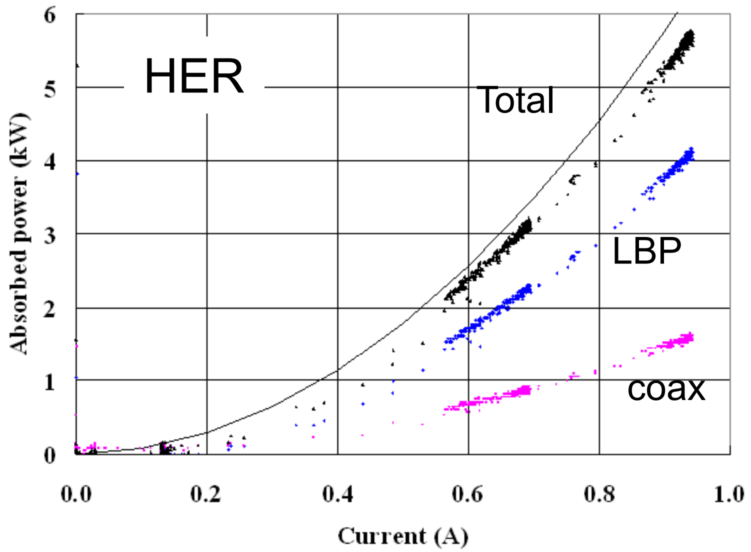
- Ferrite dampers
  - Beam pipe damper (LBP damper)
  - Coaxial damper (Coax damper)
- During the crab commissioning
  - LBP damper absorbed up to 10 kW
  - Coax damper up to 2 kW
- HOM power
  - HER: agree with calculation
  - LER: 60 %
    - SiC damper
    - Bunch length



LER crab cavity only

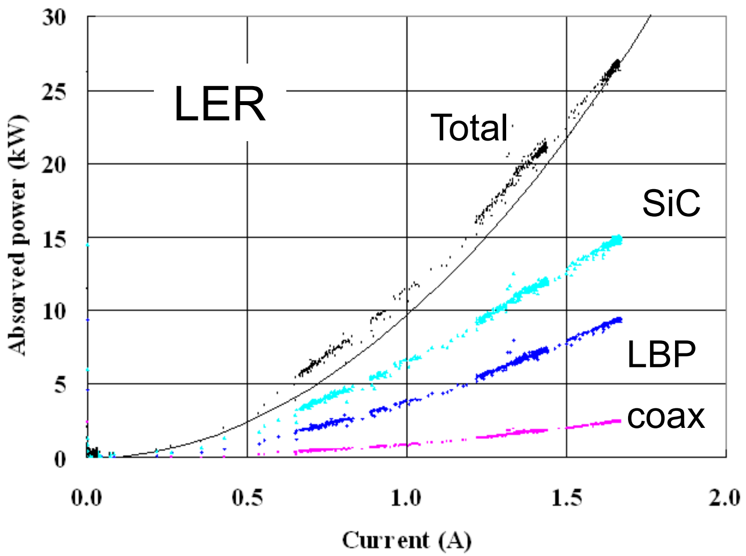


Typical HOM powers in the beam operation

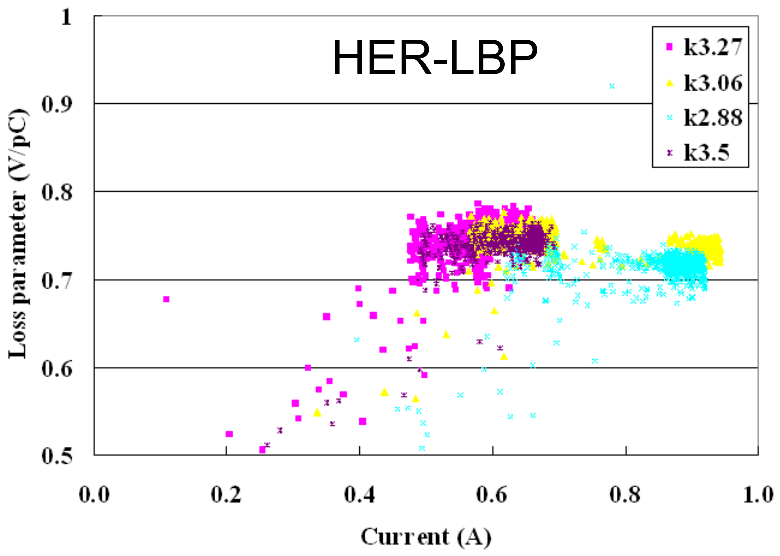


Absorbed HOM power:
4.1 kW (LBP) + 1.6 kW (coax) @ 0.95 A
Calculation well reproduces total HOM power.
Coax/LBP=0.22 for 3.5-sp
Coax/LBP=0.4 for 3.06-sp

Coaxial damper slightly higher than calculation
Several resonantly build-up RF mode increase HOM power.



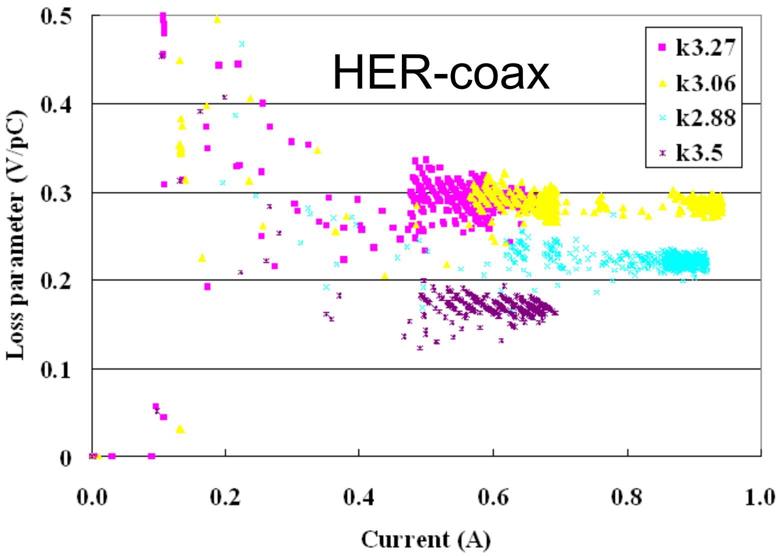
Absorbed HOM power:
9.4 kW (LBP) + 2.4 kW (coax) @ 1.62 A
Coax/LBP=0.20(LER) for 3.5-sp
Coax/LBP=0.25(LER) for 3.06-sp
Absorbed HOM power of the LBP HOM damper is significantly smaller than calculated values.
SiC damper contributes for HOM power absorption.
Calculation well reproduces total HOM power.

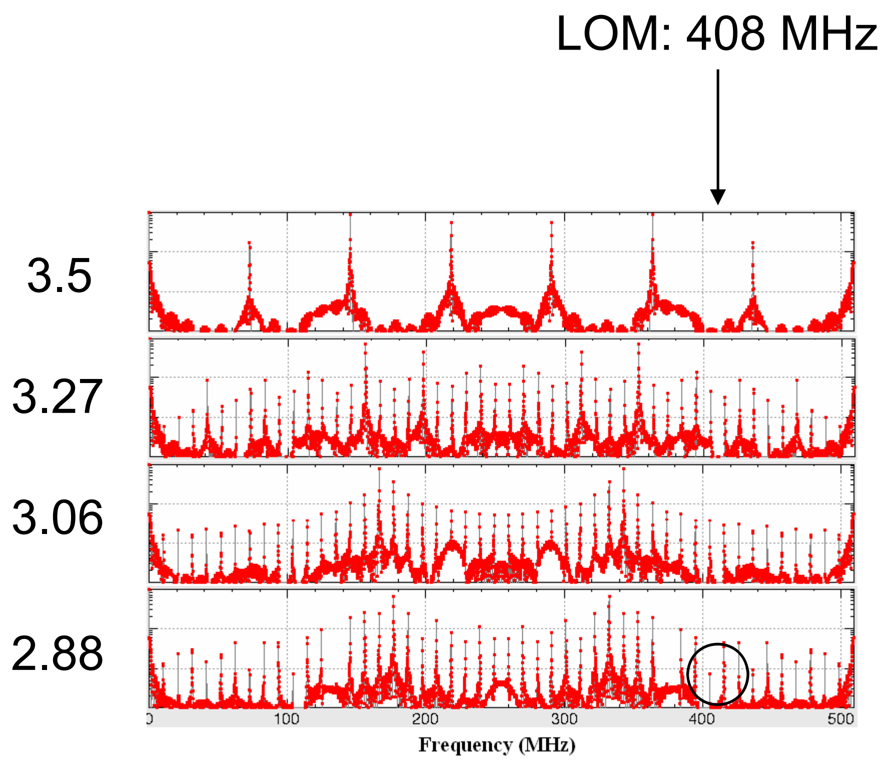


Loss parameter: k
P: HOM power
I: Current
N_b: Number of bunches
f_{rev}: Revolution frequency

$$k = \frac{P}{I^2} N_b f_{rev}$$

Calculation
LER: 0.927 V/pC
Coax: 0.2 V/pC





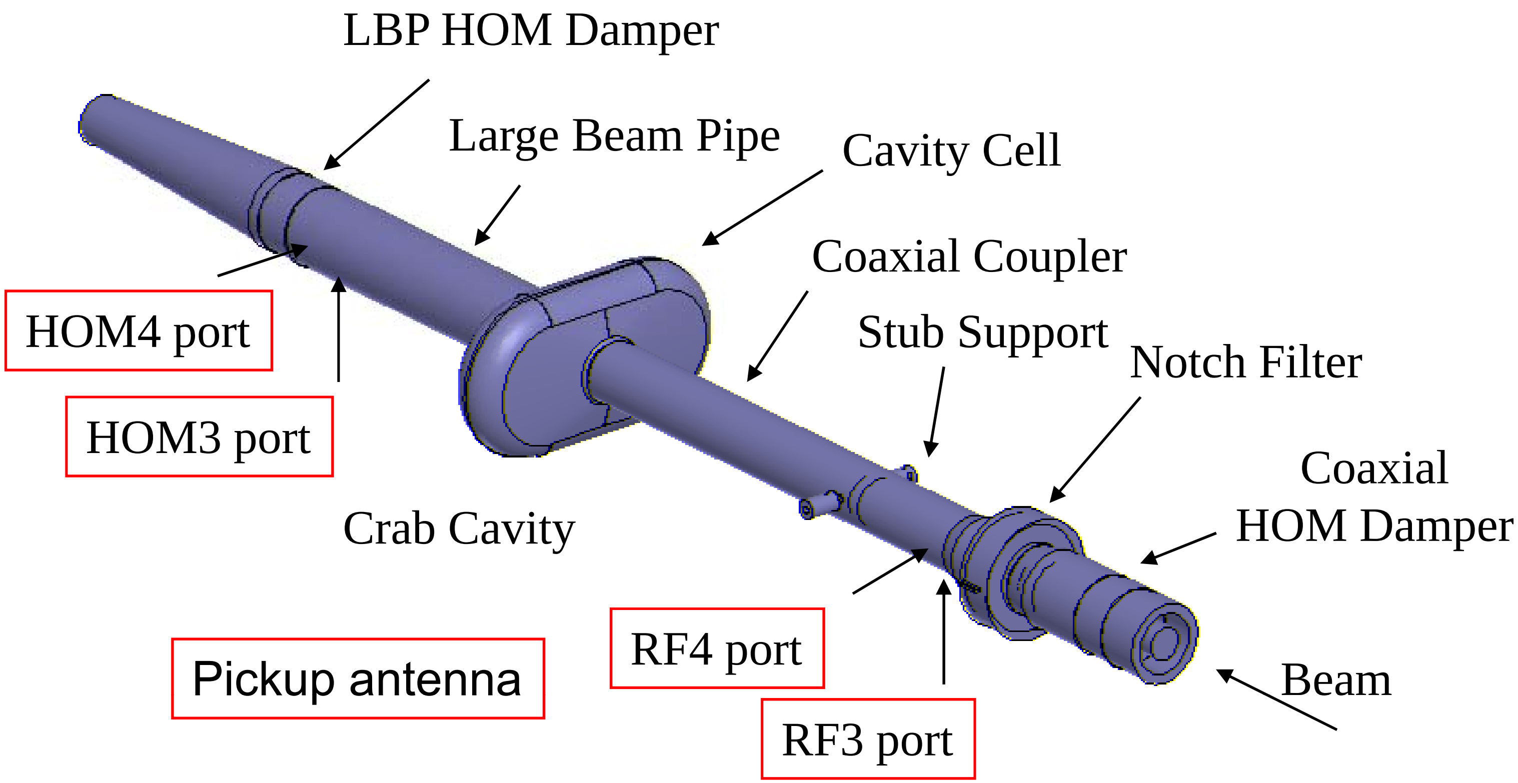
Beam spectrum

Achieved parameters during beam operation

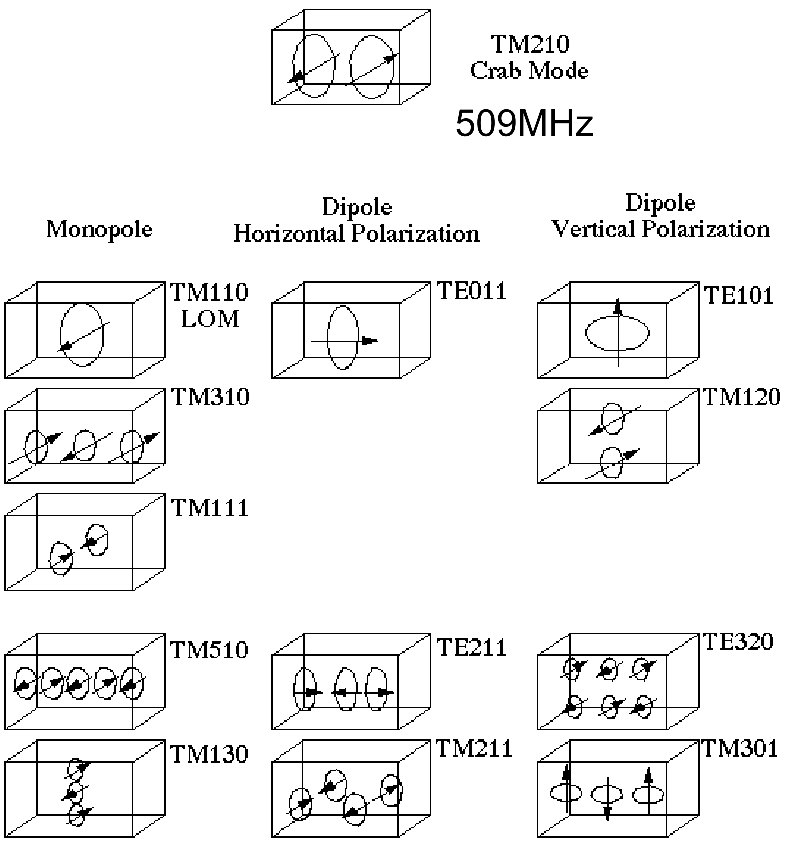
	LER	HER	unit
Beam current (Crab ON)	1620	950	mA
Beam current (Crab detuned)	1700	1350	mA
Crab voltage (max)	1.5→1.1 →1.27	>1.8	MV
Crab voltage (operation)	0.8〜0.95	1.3〜1.48	MV
HOM + LOM power	12+15(SiC)	12	kW/cavity
Tuner phase stability (w/piezo) (w/o piezo)	± 13 ± 15	± 1 ± 3	degree degree
Crab phase stability	± 0.1	± 0.1	degree
Average trip rate (1st period) (2nd period) (3rd period) Average	1.6 0.4 0.4 0.7	1.3 2.7 1.2 1.4	times/day

Beam-Induced RF spectrum

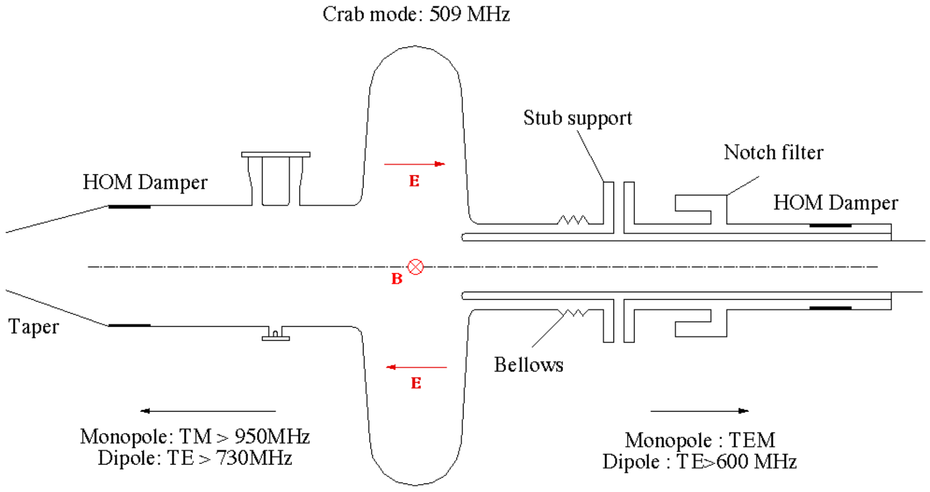
Crab cavity has several RF ports to measure beam-induced RF spectrum.
They are pick-up antennae.
Four antennae are set on the coaxial coupler.
Four antennae are set on the beam pipe.



Conceptual design of the crab cavity
(Damping scheme of parasitic modes)

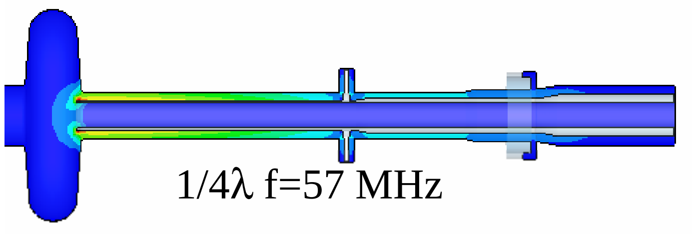


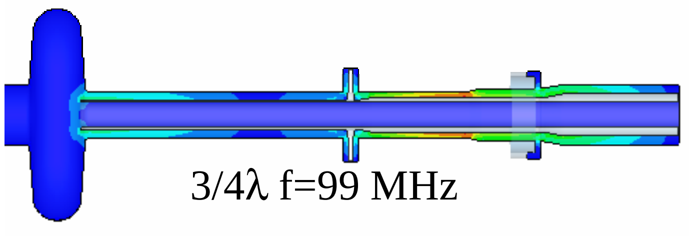
- •Monopole modes (including LOM) can propagate along the coaxial coupler.
- •Dipole modes above 600 MHz can propagate.
- •Crab mode (509 MHz) can not propagate.
- •Attenuation factor of this mode is 60 dB/m
- •If the coaxial coupler deflects, crab mode can propagate as TEM mode in the coupler.
- •Notch filter push this mode back to the cavity.
- •Stub support supports the long inner conductor.

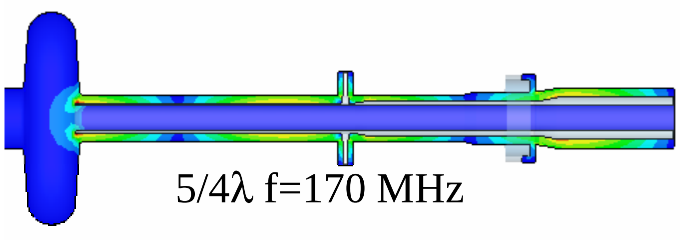


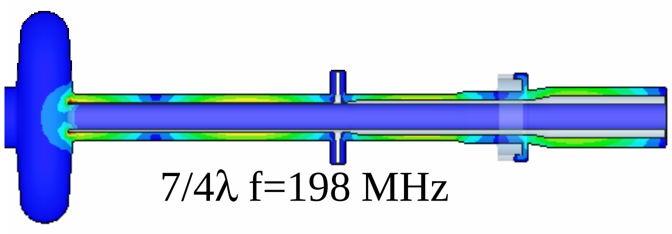
K. Akai et al, PAC 1993.

TEM modes in the coaxial









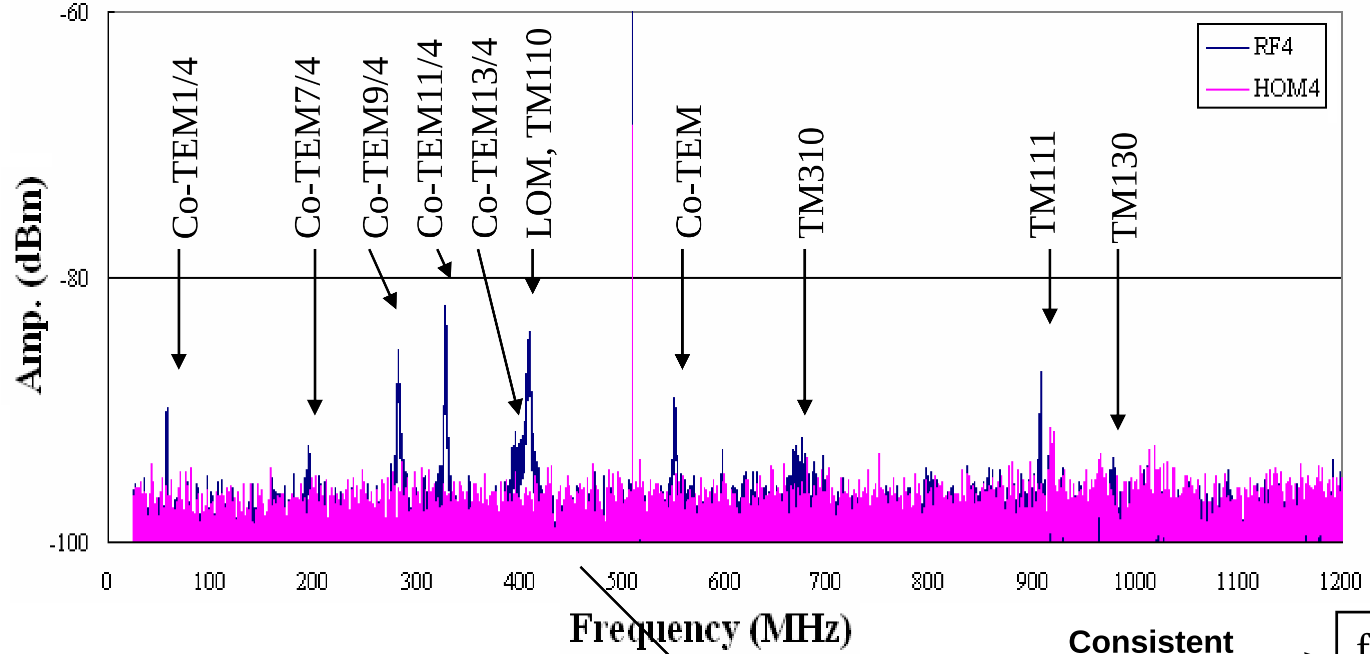
Like a quarter wave resonator, the coaxial coupler has several parasitic modes, that have frequencies below 500 MHz.

Freq(MHz)	Mode
57	co-TEM 1/4λ
99	co-TEM 3/4λ
170	co-TEM 5/4λ
198	co-TEM 7/4λ
283	co-TEM 9/4λ
327	co-TEM 11/4λ
396	co-TEM 13/4λ/TM110
440	co-TEM 15/4λ
473	co-TEM 17/4λ

Single bunch operation at a machine study

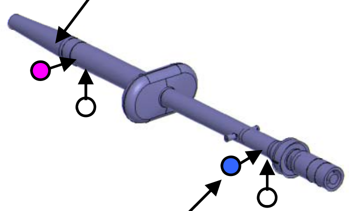
Single bunch operation is suitable to measure beam-induced RF modes since its spectrum is flat with a revolution interval (100 kHz)

6/21 LER: 0.86MV,0.48mA

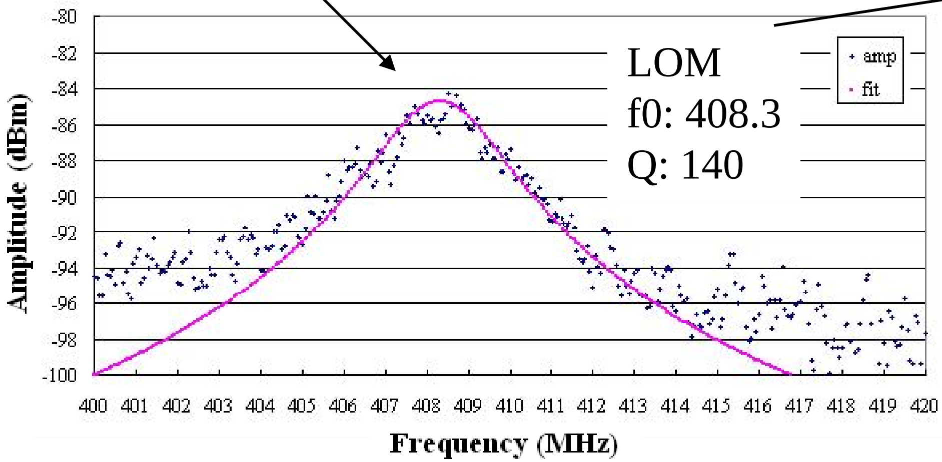


Freq(MHz)	Mode
56	co-TEM 1/4λ
195	co-TEM 7/4λ
282	co-TEM 9/4λ
327	co-TEM 11/4λ
395	co-TEM 13/4λ
408	TM110, LOM
550	co-TEM 19/4λ
672	TM310
696	TM310
907	TM111
979	TM130

Mainly observe beam spectrum.



Mainly observe beam-induced RF modes.



Consistent

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

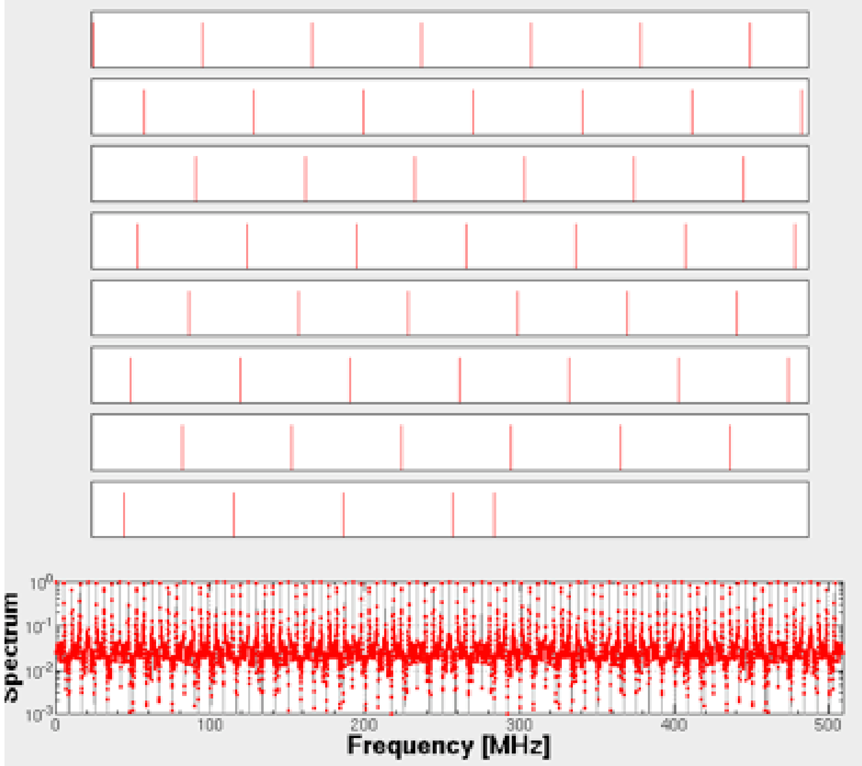
The most gengerouse mode, TM110 (accelerating mode) is heavily damped.

Bunch fill pattern

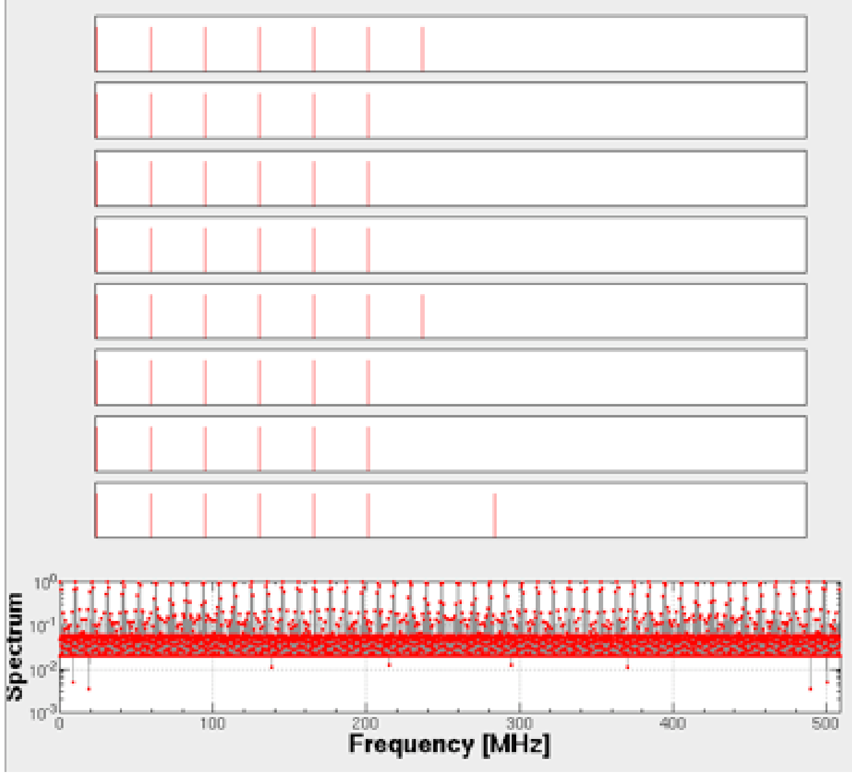
- Low current operation (30mA)
  - Number of bunches: 30 (160 RF bucket spacing)
  - Bunch current: 1 mA
  - To reach medium current operation (24.5 or 3.5 bucket spacing)
    - Avoid new HOM resonance
    - 51 bunches, 98 bucket spacing
    - 51 bunches, 49 bucket spacing, 8 trains
- Medium current operation (200mA)
  - Number of bunches: 200 (24.5 RF bucket spacing)
    - 7 bucket spacing, 8 trains
    - 3.5 bucket spacing, 8 or 16 trains
- High current operation (1.7 A (LER) x1.3 A (HER))
  - Number of bunches: 1389 (3.5 RF bucket spacing)
  - Bunch current >1 mA
- In the 2^{nd} and 3^{rd} period
  - Specific luminosity decreases as the bunch current increases.
  - To increase luminosity, bunch fill patterns with a smaller RF bucket spacing were applied.
    - small bunch current and large number of bunches
    - 3.5 sp (1389 bunches), 3.27(1485), 3.06(1585), 2.88(1678)

Example of bunch fill pattern

51 bunches, 98 bucket spacing

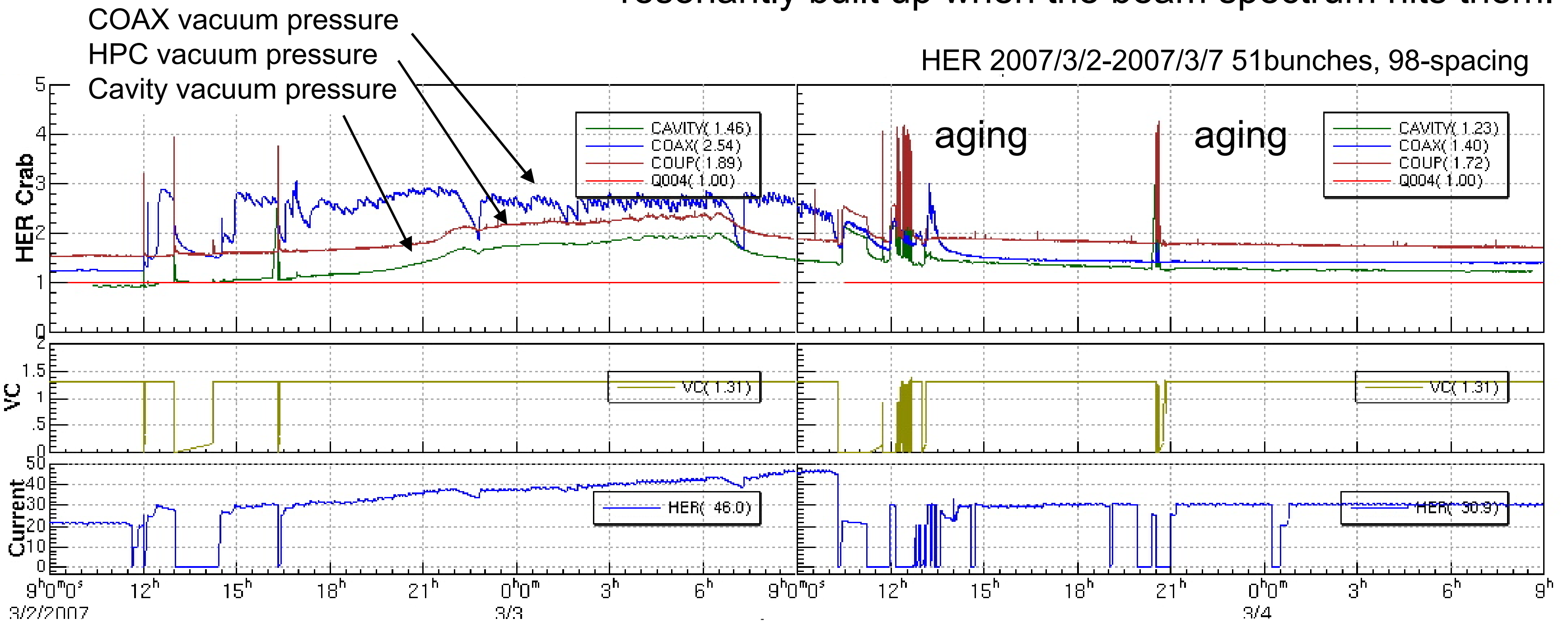


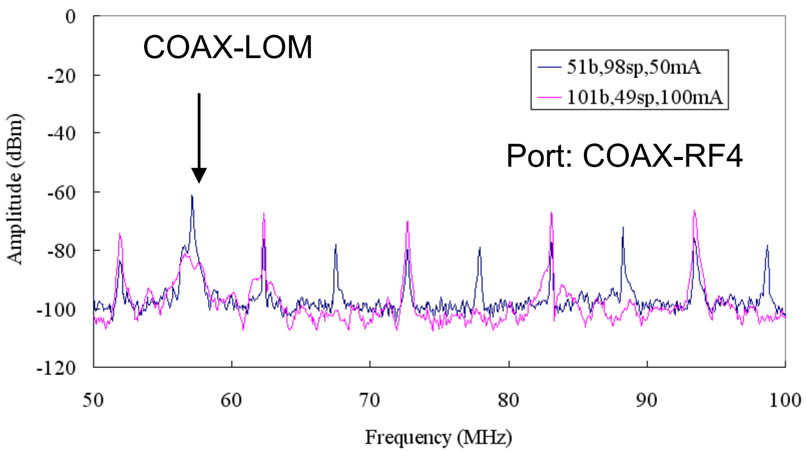
51 bunches, 49 bucket spacing x 8 trains

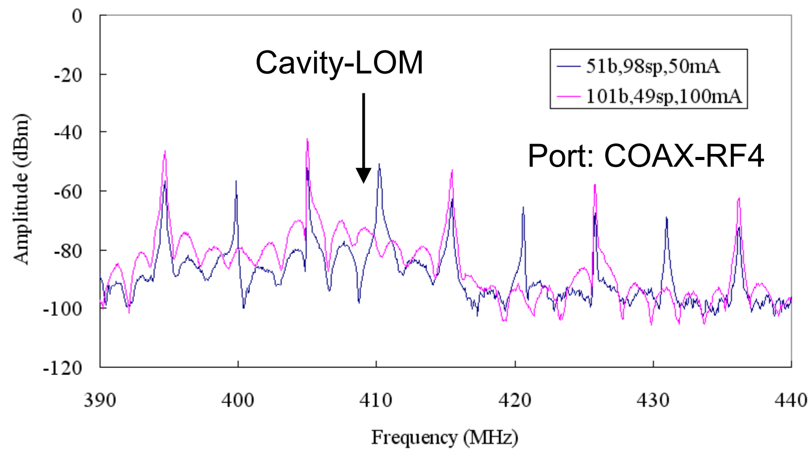


Effect of bunch fill pattern

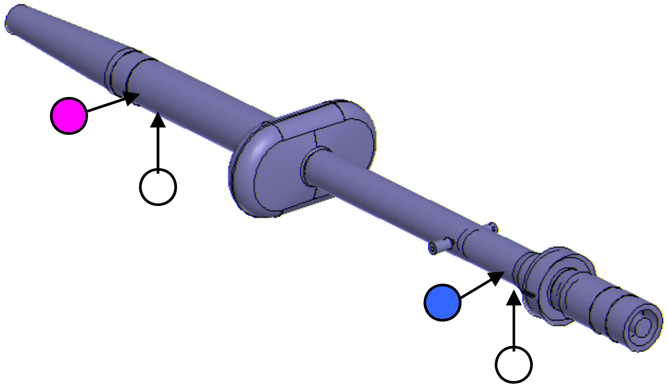
LOMs are heavily damped, however, they can be resonantly built up when the beam spectrum hits them.



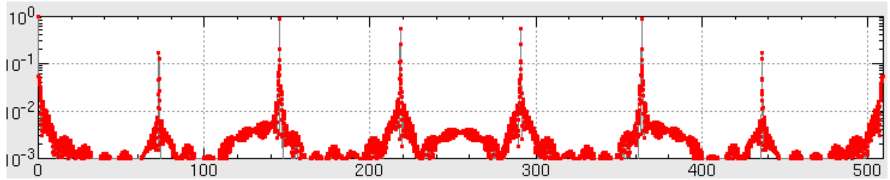




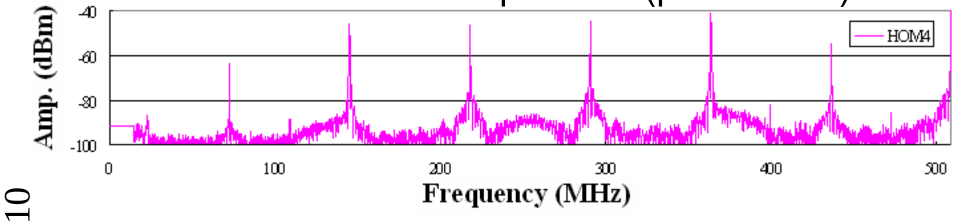
1389 bunches with 3.5 bucket spacing

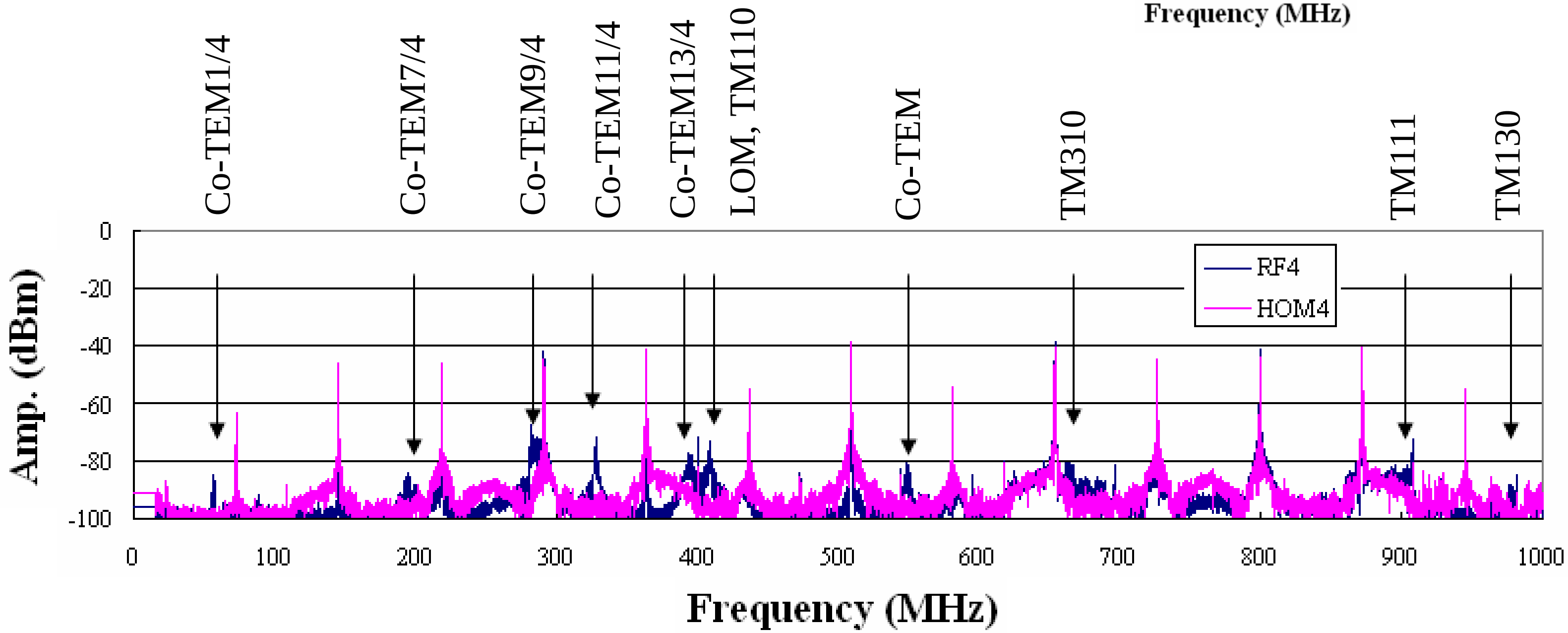


Beam spectrum

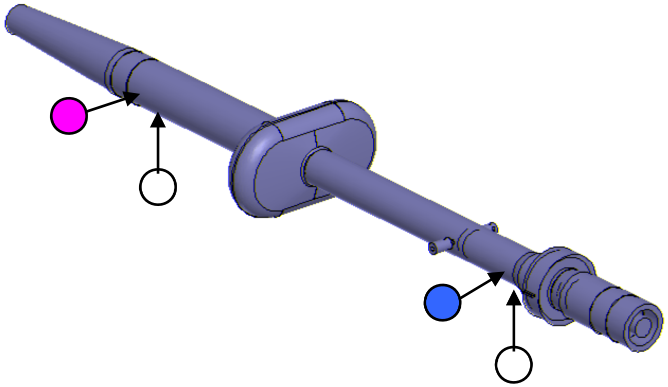


Beam-induced spectrum (port HOM4)

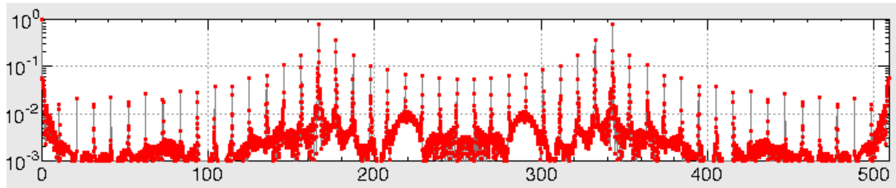




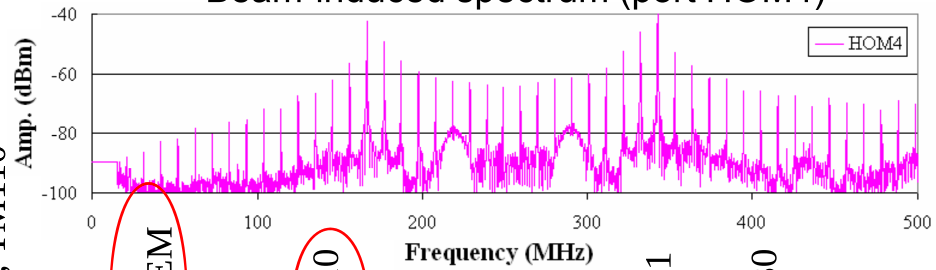
1389 bunches with 3.06 bucket spacing

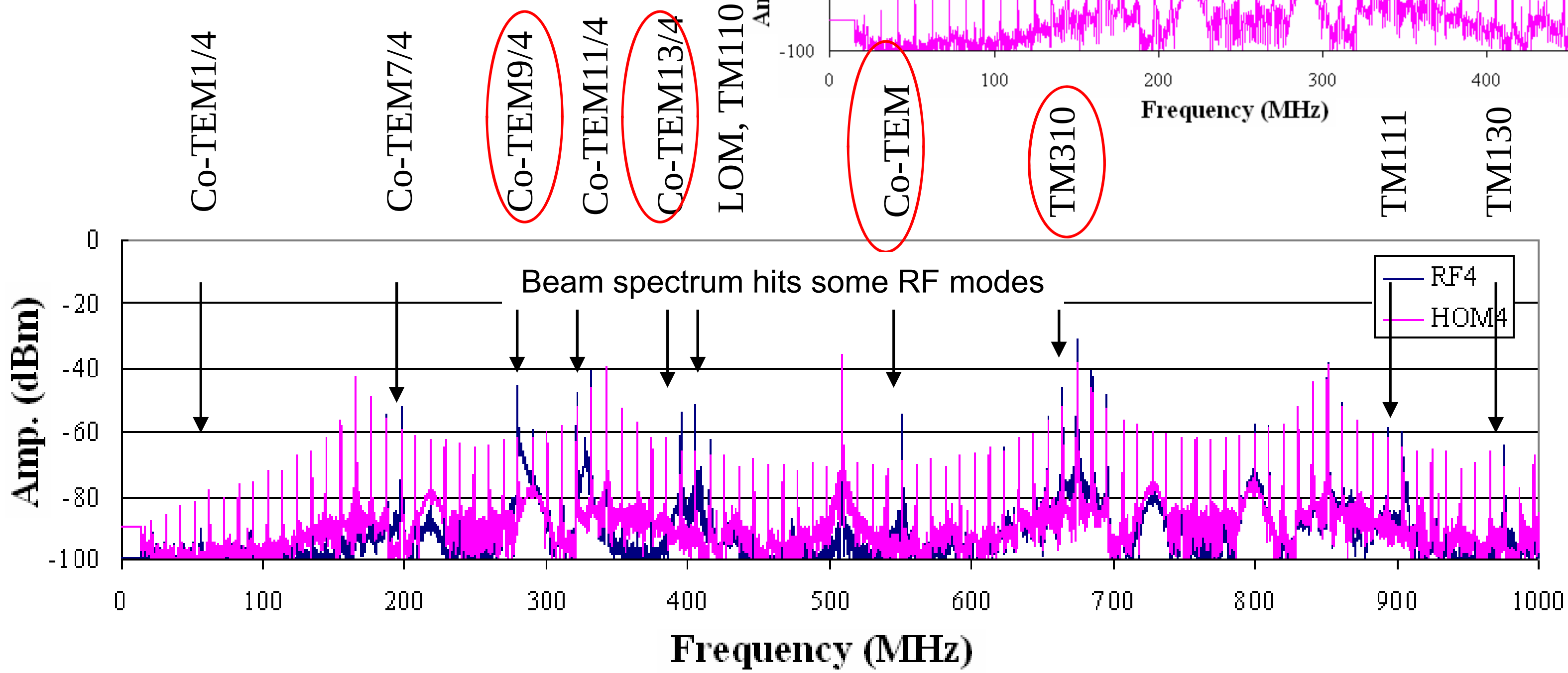


Beam spectrum

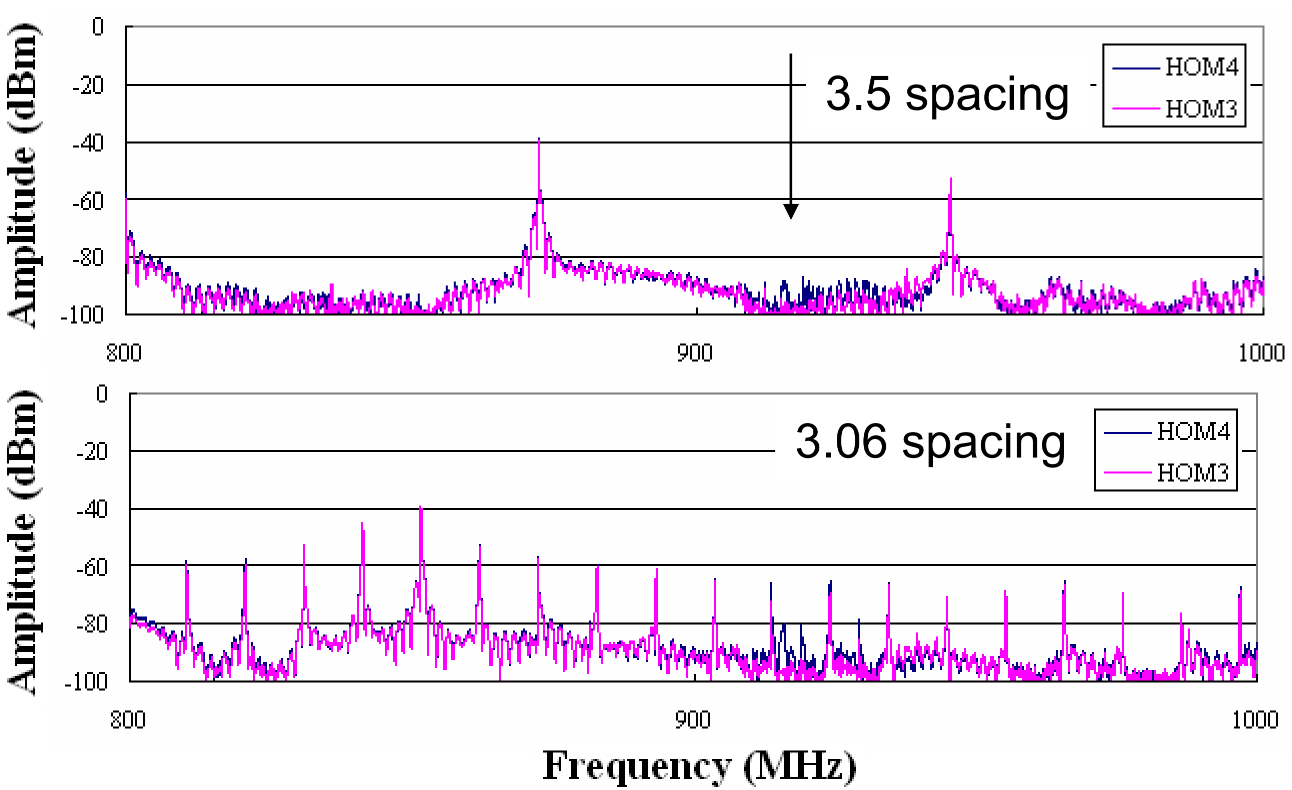


Beam-induced spectrum (port HOM4)

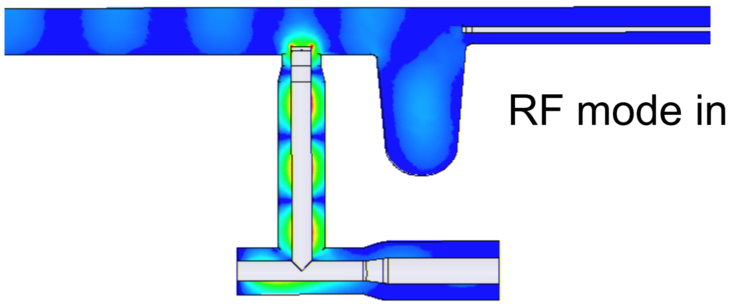




Coupler mode excitation



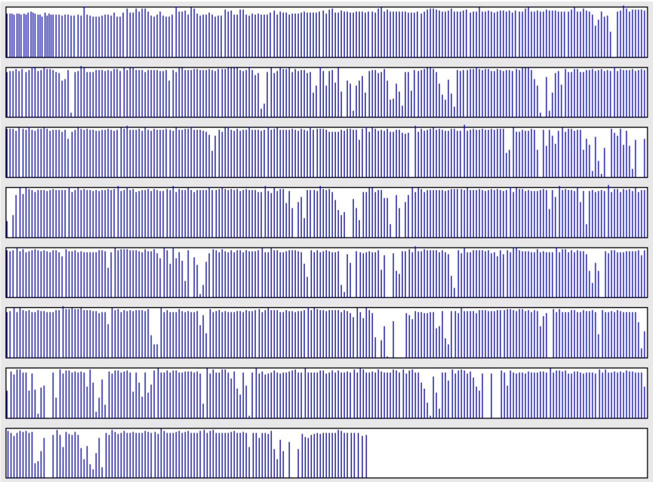
Horizontally inserted antenna on the beam pipe (HOM-H) observes Horizontally polarized TE mode in the beam pipe. This mode is a RF mode in the stub-type high power coupler.



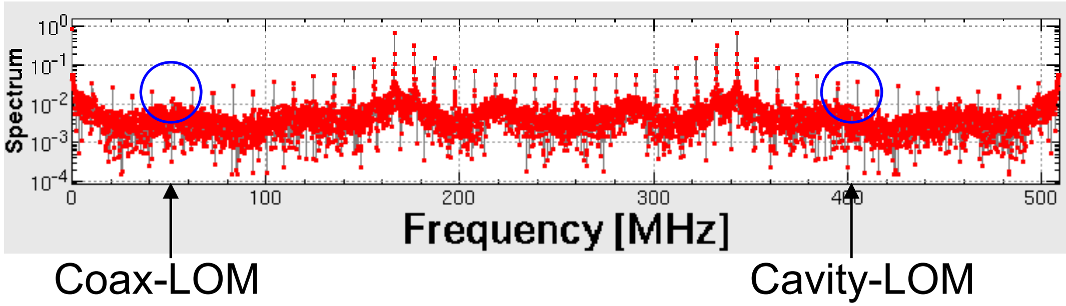
RF mode in the stub-type HPC

Cavity trip due to unbalanced beam filling

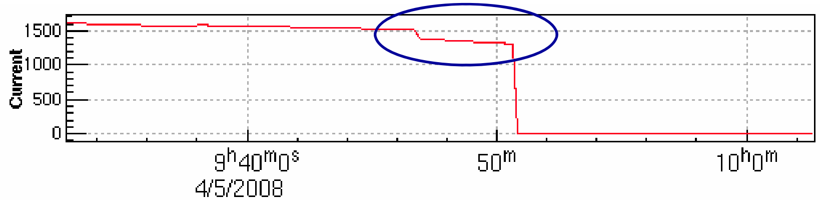
Unbalanced beam filling

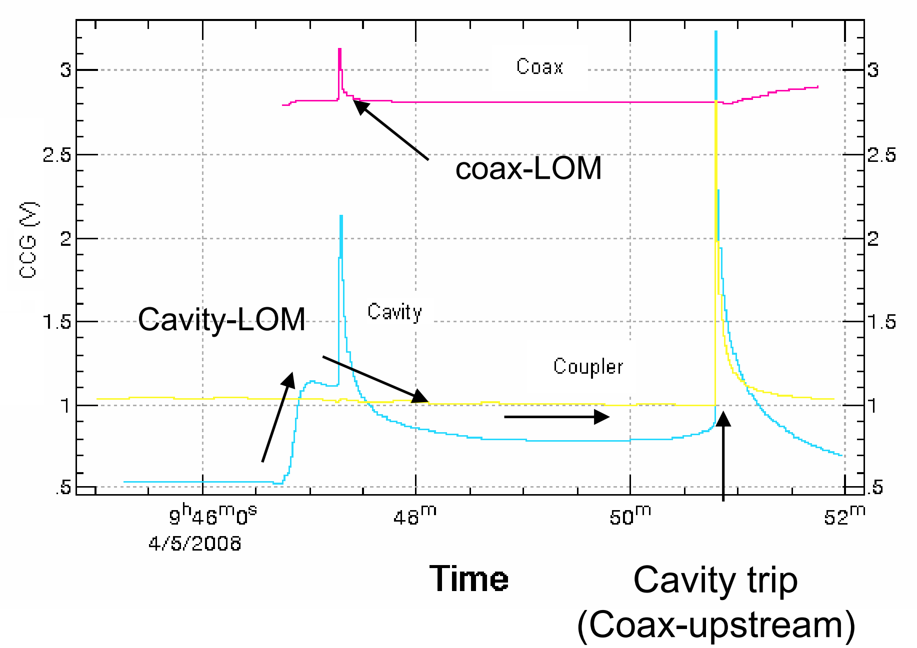


Its spectrum



LER current





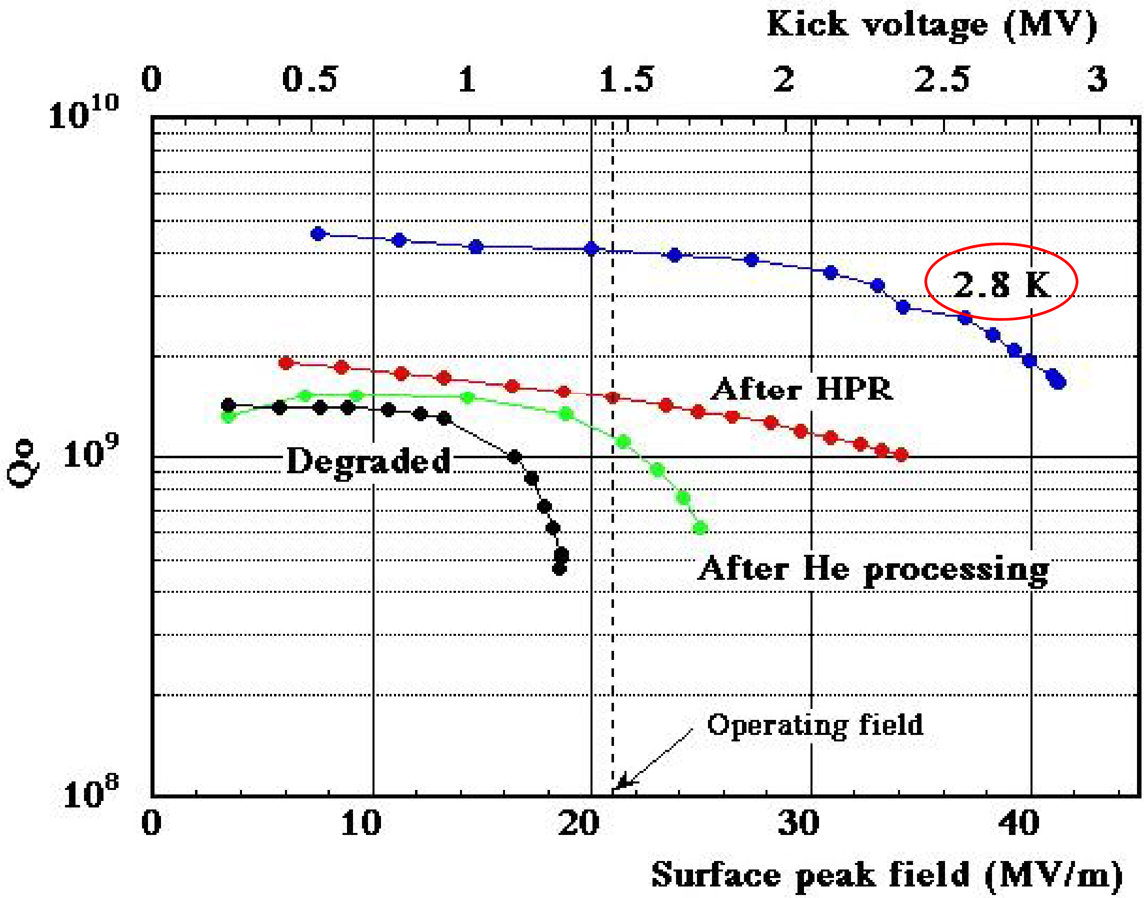
- Beam loss results in unbalanced beam filling
- Deform beam spectrum
- Coax-LOM and Cavity-LOM are built up
- Increase vacuum pressure
- Induce multipacting in the coaxial coupler
- Lead cavity trip

Need for higher Vc

- Large beta function at crab cavity causes beam loss.
- Using coaxial coupler, physical aperture is limited to ~100 mm.
- Need for higher Vc for lowering beta.
  - Low temperature operation may improve.

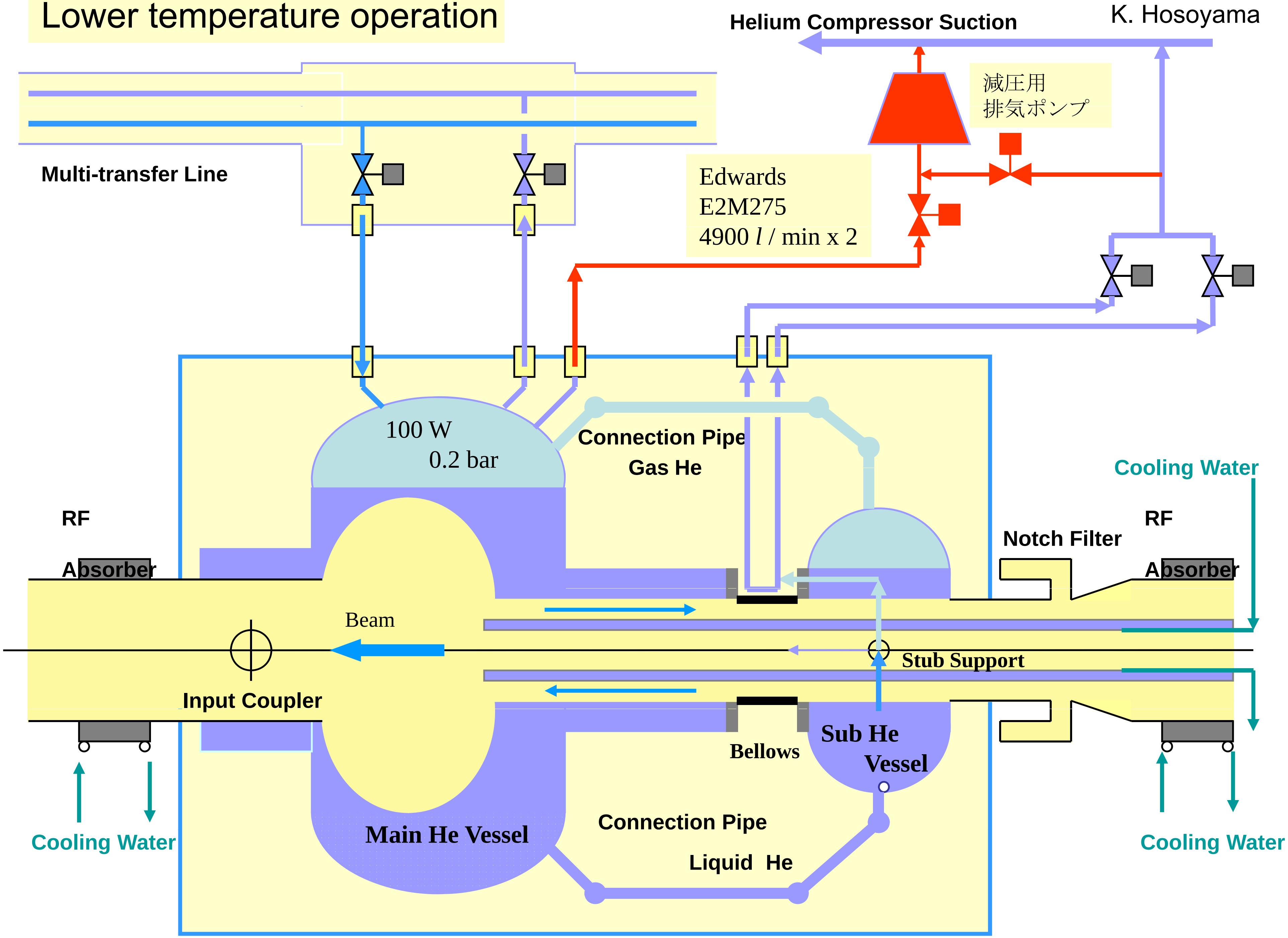
Cavity performance at lower temperature

Vertical Cold Test (prototype cavity)



Lower temperature operation

K. Hosoyama



Summary

- High beam currents (1.7/1.35 A) were stored with crab cavities.
- No serious beam instabilities caused by LOM/HOM were observed.
- HOM powers were successfully absorbed up to 12 kW in the ferrite dampers.
- Physics run with CRAB ON with high beam currents (1.62/0.95 A).
  - Peak luminosity: 16 /nb/s
- LER crab voltage degraded to 1.1 MV (recovered to 1.27 MV).
  - Still applicable by increasing beta-x at the LER crab cavity.
- Crab phase was well controlled, although the LER tuner phase has large fluctuation.
- 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(LER)/1.2(HER) par day (3rd period).
- KEKB crab cavities have been working with high beam currents to conduct physics run with the crab crossing !!
- We are preparing for the low temperature operation.