RF system for crab cavity

1. Beam-loading issues
2. Tolerance for phase error
3. Construction status

K. Akai for KEKB-RF group

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Beam-loading on crab cavity

2.2 Vector relations

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

In the following, a positron beam ($q > 0, I_b > 0$) is considered. (An electron beam can be treated similarly.) Figure 1 shows a vector relation for the crabbing mode. In this figure, $V_{\perp g}$ is the generator voltage, $V_{\perp gr}$ the generator voltage on resonance, α_L the angle between $V_{\perp gr}$ and $V_{\perp c}$, and ϕ_c the angle of $V_{\perp c}$ with respect to the beam. It is similar to that for the accelerating mode, except for the beam-induced voltage, $V_{\perp br}$ and $V_{\perp b}$. The phase of $V_{\perp br}$ with respect to the bunch phase is 90 or 270 degrees, according to $\Delta x < 0$ or $\Delta x > 0$ (180 degrees for the accelerating mode). Furthermore, the amplitude of $V_{\perp br}$ is dependent on Δx.

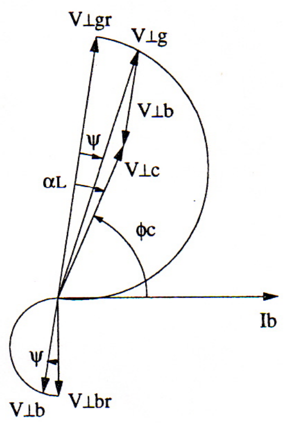


Figure 1: Vector relation for the crabbing mode ($\Delta x > 0$).

From the vector relation we obtain

$$\tan\alpha_L = \frac{\tan\psi - Y\cos\phi_c}{1 + Y\sin\phi_c}, \quad (6)$$

$$|V_{\perp gr}|\cos\alpha_L = |V_{\perp c}|(1 + Y\sin\phi_c), \quad (7)$$

where $Y \equiv \pm |V_{\perp br}/V_{\perp c}|$ (positive sign for $\Delta x > 0$ and negative sign for $\Delta x < 0$).

Since $|V_{\perp gr}|$ is related to the input power (P_g) as

$$|V_{\perp gr}| = \frac{2\sqrt{\beta}}{1+\beta}\sqrt{\bar{R}_\perp P_g}, \quad (8)$$

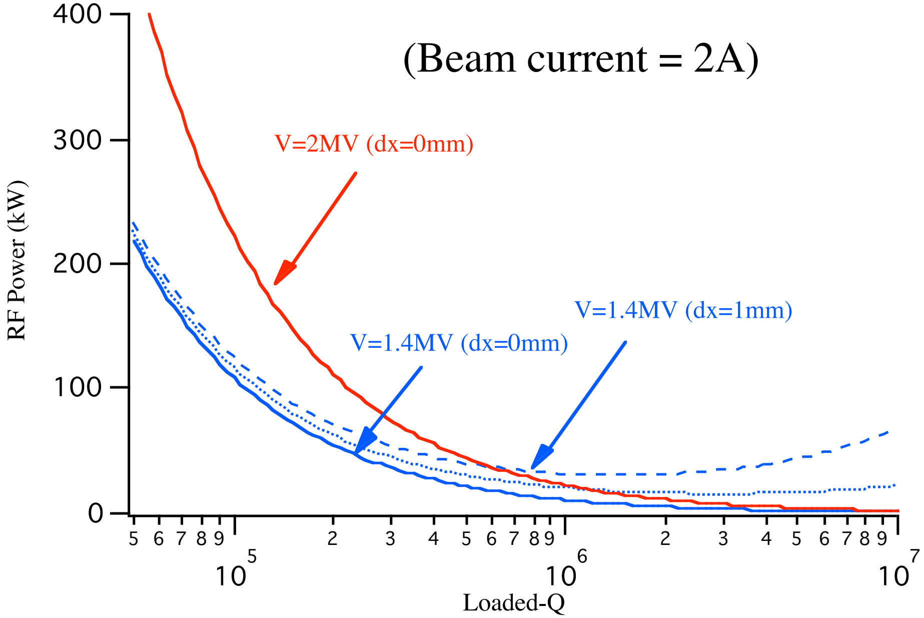
the required power to maintain the crabbing voltage is obtained from Eqs. 4, 7 and 8 as

RF Power

$$P_g = \frac{(1+\beta)^2}{4\beta\bar{R}_\perp} \times \left\{\frac{1}{\cos\alpha_L}\left(|V_{\perp c}| + \frac{I_b\bar{R}_\perp}{1+\beta}k\Delta x\sin\phi_c\right)\right\}^2. \quad (9)$$

Kick voltage *Beam orbit offset (Δx)*

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.

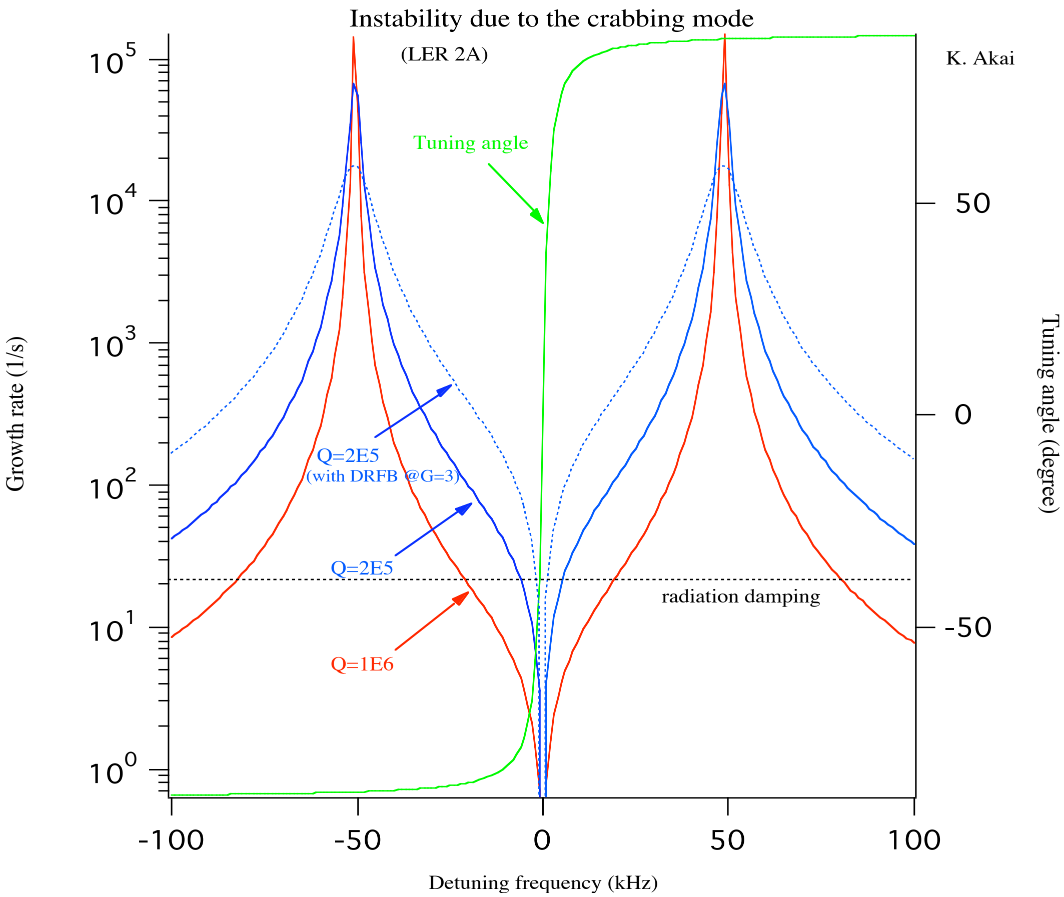
- Beam-induced voltage:

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

  - 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 2MV.
  - 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 by Masuzawa-san.

CBI due to the crabbing mode

Growth rate



- Crabbing mode operation
  - Crab cavity is operated just on resonance.
  - Growth rate is smaller than the radiation damping rate even at a tuning error of +/- 30 degrees.
- When parked away from RF frequency
  - Should be kept away from every half revolution frequency (horizontal tune is half integer).
  - Still, growth rate can be higher than the radiation damping. CBI should be cured by bunch-by-bunch feedback.

Phase Tolerance

- RF phase error (timing error) gives rise to a horizontal displacement at the IP.

$$c\Delta t \leq A\sigma_x^* / \phi_{cross}$$

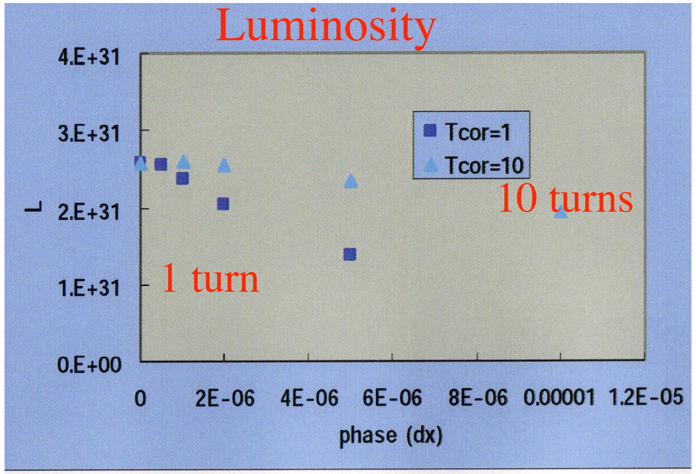
  - Here, ϕ_{cross} is the half crossing angle.
  - A is the ratio of allowed offset to horizontal beam size, σ_x*. The value A should be determined from the beam-beam point of view.

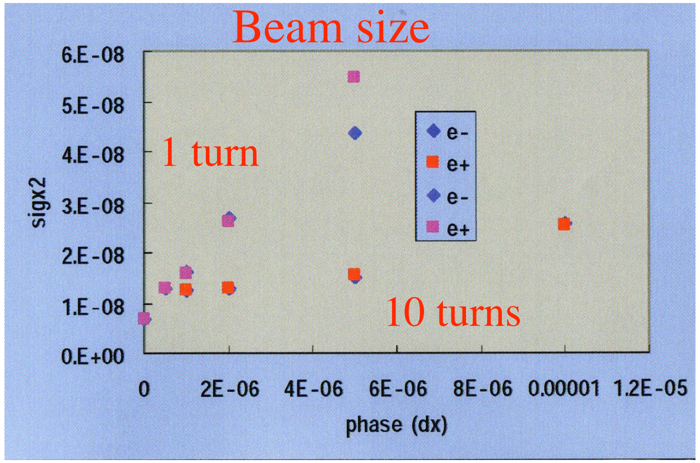
	KEKB	Super-KEKB	LC
σ_x*	100μm	70μm	0.24μm
A (assumed)	0.05?	~0.05?	~0.2?
ϕ_{cross}	+/- 11mrad	+/- 15mrad	+/- 3.5mrad
Δt	1.5 ps	0.8 ps	0.05 ps

0.27 deg (509MHz)

Effect of RF phase jitter on the beam-beam performance

- Tolerance is different according to correlation time (Ohmi and Tawada).
  - For the correlation time of 10 turns, 5 microns is allowed.
  - For the correlation time of 1 turn, tolerance is only 1 micron.
- How fast is the correlation time in KEKB?
  - Possible change, if any, will be slower than the filling time of accelerating cavities (2～3 turns) or crab cavities (12 turns).
  - Fast change in several turns has not been observed except modulation due to abort gap.
  - Then, a displacement of 5 microns (phase error of 0.27 degree) is allowed.





Source of phase error and cure

- Slow phase drift due to temperature change, etc.
  – CCC (continuous closed orbit correction system) can tell the amount of single kick caused by the phase error of crab cavities (Koiso-san).
  – It can be easily compensated using a low-level phase shifter.
- Fast phase errors
  – As shown, a displacement of 5 microns is allowed, corresponding to a phase error of 0.27 degree.
    - Measured phase error in the present RF reference line is about 0.03 degree.
    - Accuracy of cavity phase control will be measured in the horizontal test.
    - Phase error caused by beam-induced voltage is small at a moderate orbit error.
  – No clear problem is seen so far. More information is needed in operation.
- Abnormal phase change due to a trip of crab RF station
  – The amplitude and phase can not be controlled when a trip occurs.
  – The beam must be aborted as fast as possible (can not survive anyway?).

Transient due to abort gap

- Phase modulation in a bunch train
  - depends on parameters such as RF voltage, Q_L, beam current, gap length.
- Relative displacement is mostly compensated,
  - since the same direction in both rings.
- How about residual?
  - Residual is +/- 7 μm for head and tail bunches of a train.
  - Constant for each bunch. This amount of residual is not disastrous for the correlation time of more than ten turns.
  - Current ratio may need to be optimized to minimize the residual.

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

Table 2: Bunch position shift due to 5% gap in both rings.

	LER	HER
Current [A]	2.6	1.1
Phase modulation (p-p) [deg]	3.5	2.7
Δ z (p-p) [mm]	5.7	4.4
Δ x at CP (p-p) [mm]	0.063	0.049
Δ z (relative) † [mm]	± 0.3	
Δ x (relative) †† [mm]	± 0.007	

† $(\Delta z_{\rm her} - \Delta z_{\rm ler})/4$ and †† $(\Delta x_{\rm her} - \Delta x_{\rm ler})/2$

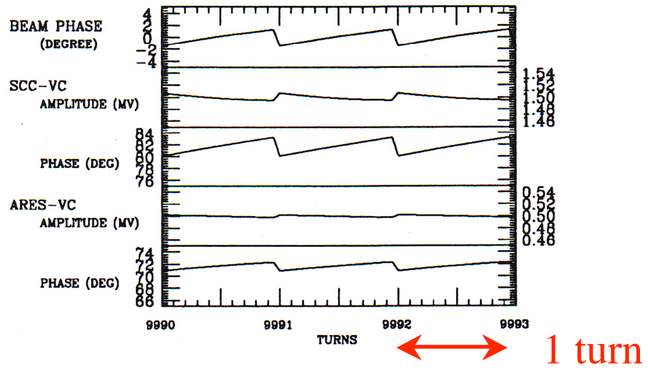
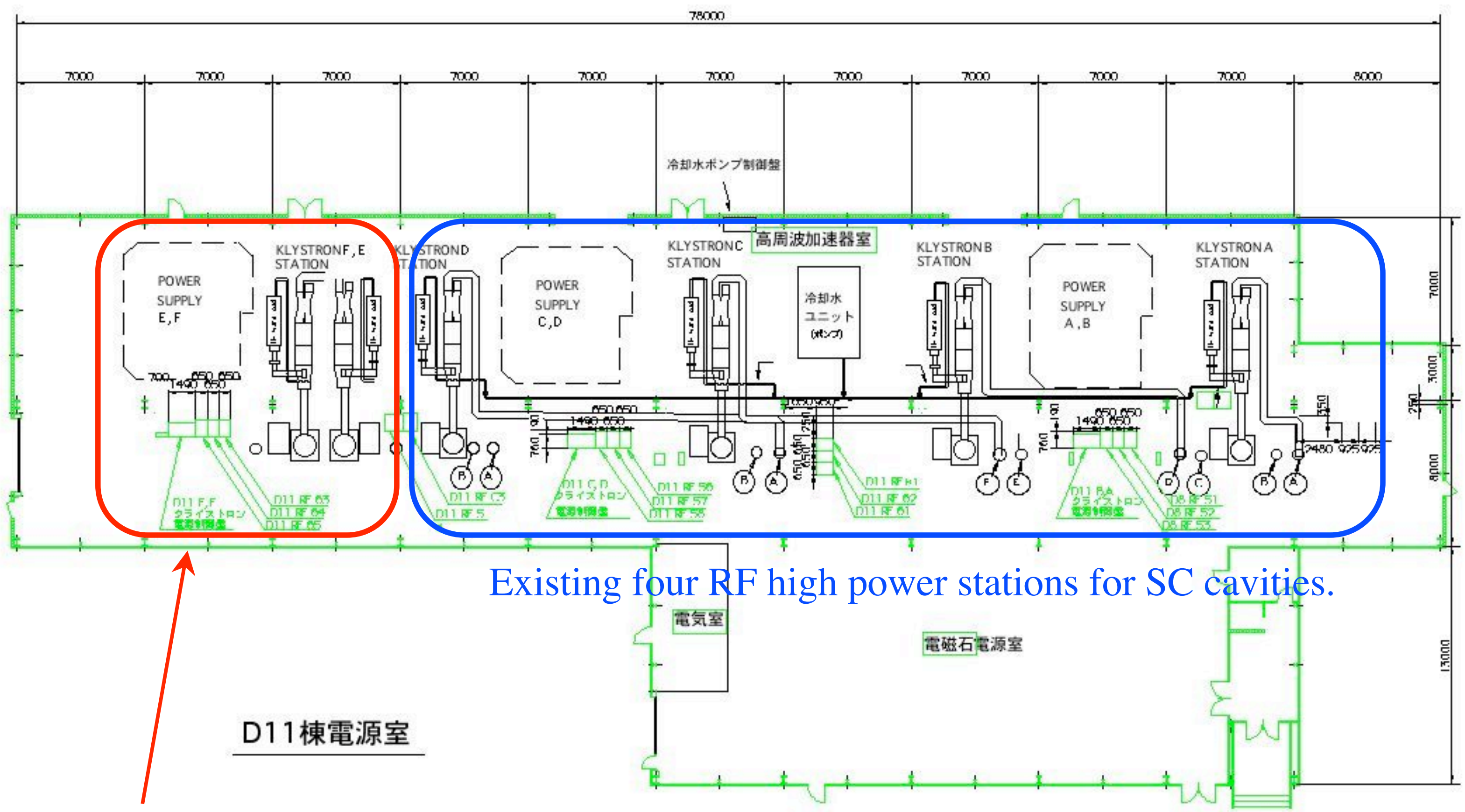


Figure 3: Transient response of the hybrid system in HER to a 5% gap.

Construction of crab RF stations

- Two new RF stations have been built in D11 for the crab cavities.
  - D11-E for the LER crab cavity.
  - D11-F for the HER crab cavity (cavity is in D10 tunnel).
  - Required power is 200 kW, much lower than the existing stations for accelerating cavities.

Layout of D11 klystron gallery



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

Klystron and power supply

- Klystrons
  - Two reused klystrons have been conditioned up to 600 kW at D2 test stand, enough for crab cavities.
  - They have already been installed at D11.
- Power supply for klystrons
  - A spare power supply for one klystron was modified to drive two klystrons.
  - Moved to D11 and set up completed.
  - System check applying HV to the klystrons was successfully done.
- Ready for high power RF operation.

Two Toshiba klystrons

Power supply for the klystrons

High power RF system

- Construction of major part completed.
  - Waveguides on the ground level have been built. Long path (~100m) of waveguide connection in the tunnel from D11 to D10 is finished.
  - 1MW circulators and dummy loads have been installed.
  - Vapor cooling system for the klystrons is common to the existing D11 RF stations for SCC: no need for major change.
  - Construction is finished except final connection of waveguides to cavities.

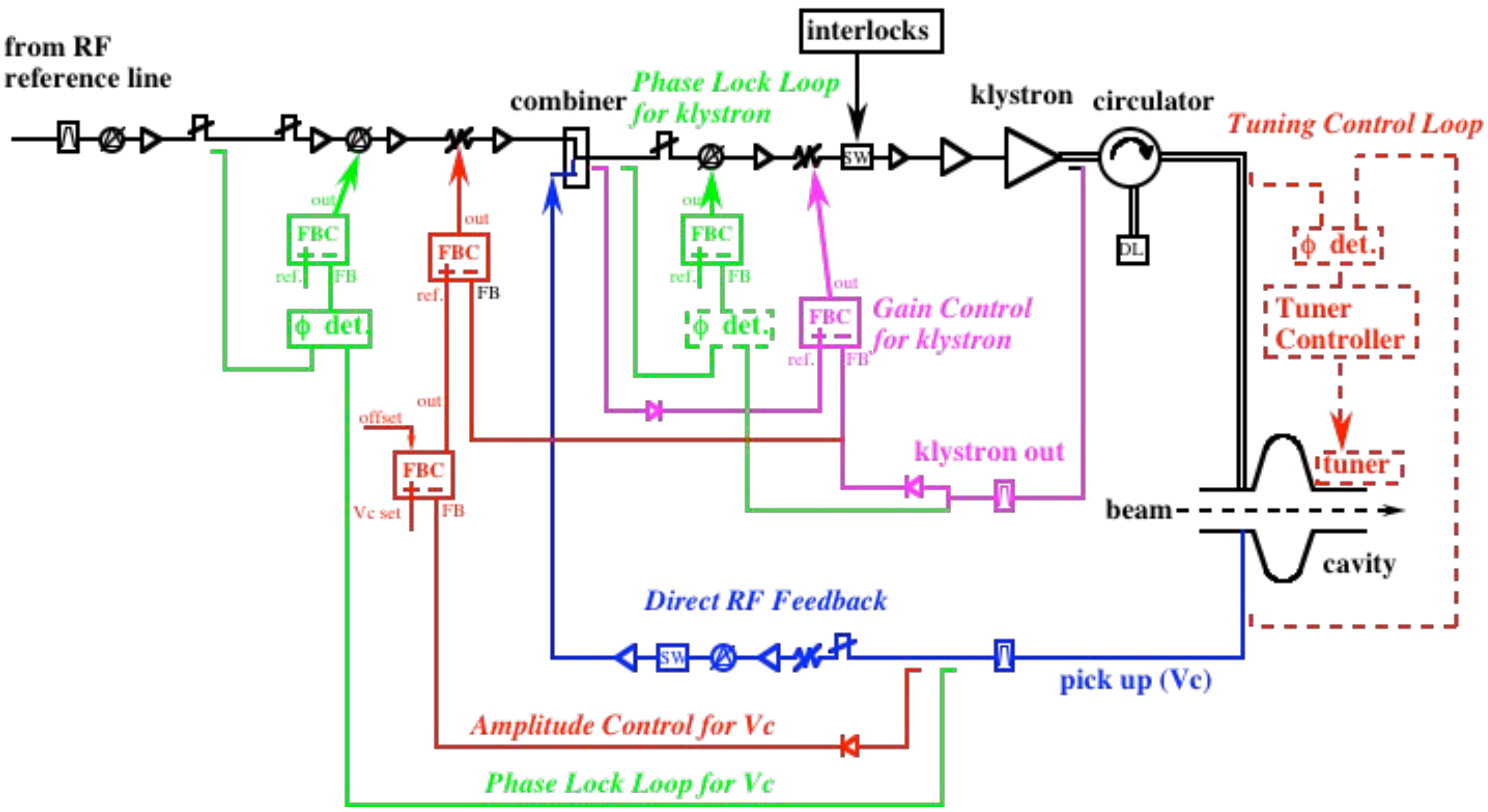

350
500
370
370
350
350
250
450
250
350
350

Low-Level RF system

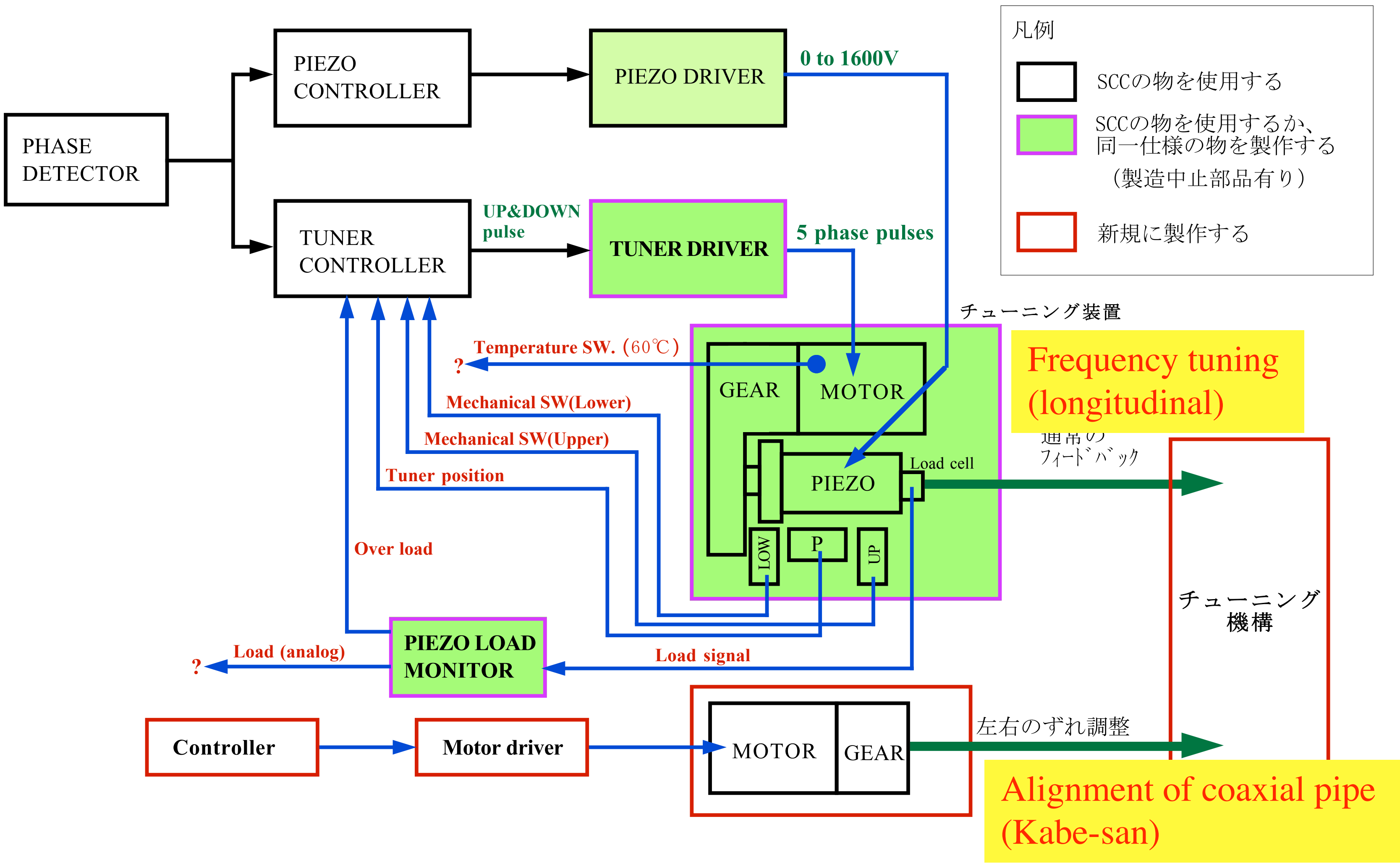
- RF control hardware
  - Mostly similar to the low-level system for the SC accelerating cavities.
    - Feedback loops, interlocks, monitor and data logging, etc.
  - Tuning system
    - Piezo and stepping motor are used for frequency tuning as SCC.
    - Horizontal position of coaxial beam pipe can be adjusted using another tuner to avoid coupling of the crabbing mode into the HOM damper.
  - Installation of RF control modules and cable connection have been done.
  - System adjustment is being done now.
- Operation software
  - EPICS records have been made.
  - Modification of application software in progress.

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

Low-level RF for KEKB Superconducting cavity



RF system for crab cavity will be similar.



PHASE DETECTOR
PIEZO CONTROLLER
PIEZO DRIVER
0 to 1600V
TUNER CONTROLLER
UP&DOWN pulse
TUNER DRIVER
5 phase pulses
凡例
SCCの物を使用する
SCCの物を使用するか、同一仕様の物を製作する
（製造中止部品有り）
新規に製作する
チューニング装置
Frequency tuning (longitudinal)
Temperature SW. (60℃)
?
GEAR
MOTOR
Mechanical SW(Lower)
Mechanical SW(Upper)
Tuner position
PIEZO
Load cell
ﾌｨｰﾄﾞﾊﾞｯｸ
LOW
P
UP
Over load
チューニング機構
PIEZO LOAD MONITOR
Load (analog)
?
Load signal
Controller
Motor driver
MOTOR
GEAR
左右のずれ調整
Alignment of coaxial pipe (Kabe-san)

Work remaining to do

- Performance of the control system for crab cavity will be checked in the horizontal test.
  - Tuning control, feedback loops, quench detector, etc.
- High power RF operation without cavities will start at the beginning of April.
  - HV has already been applied to klystrons.
- The RF system will be commissioned with crab cavities in the tunnel.

Summary

- RF system for the crab cavities has been investigated to meet the requirements for KEKB.
- Construction of two new high power RF stations for the crab cavities is completed. Final adjustment of RF control system will be done in April.

Appendix 1/4

(answer to the question yesterday)

- Dipole cut-off frequency in the coax is set as:
  - crabbing mode < cut-off frequency < any parasitic dipole mode in the cavity
- Parasitic modes are well extracted to HOM damper
  - All monopole modes including the Lower-Frequency mode (accelerating mode) are heavily damped.
  - All dipole modes except the crabbing mode are also heavily damped.
  - 1/4 wave length mode have been partly solved so far (Y. Morita-san talk).
- The effect of coax on the crabbing mode
  - Provided that the coaxial pipe is aligned perfectly on axis, there exists dipole coupling only. The crabbing mode attenuates in the coax at -60 dB/m. Thus it is confined in the cavity cell. In this case no need for the notch filer.
  - Misalignment of the coax can give rise to monopole coupling for a part of the stored energy. It propagates in the coax as a TEM mode without attenuation.
  - Notch filter rejects the TEM component of the crabbing mode back to cavity cell.

Appendix 2/4

- Effect of misalignment of the coax
  - A part of stored energy couples as monopole-like to the coax. It propagates as a TEM wave.
  - Heat load in the cryostat may increase.
  - A large power goes to HOM damper at the end of coax.
- Measurement of 1/3 scale copper cavity
  - From the reduction of loaded Q value, external-Q value is evaluated. For the displacement of +/- 1mm (3mm for 1/1 scale), Q_{ext} is about 10^6.
- Notch filter to solve the problem
  - With appropriate tuning, 30dB reduction can be obtained.
  - Position of the notch filter has been optimized to further reduce the coupling between coax and cell.
  - Then Q_{ext} is raised to the order of 10^9 even with a 3mm displacement. Leaked power to the HOM damper will be less than 100 W. It is tolerable for the damper (OK with even 1 kW). The increase of heat load in cryostat is also tolerable with the powerful refrigerator of KEKB.

K. Akai et al, Proc. B-factories, 1992

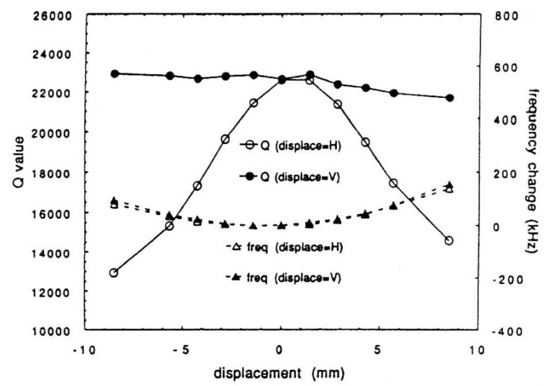


Figure 7. Effect of the misalignment of the coaxial beam pipe on the crabbing mode

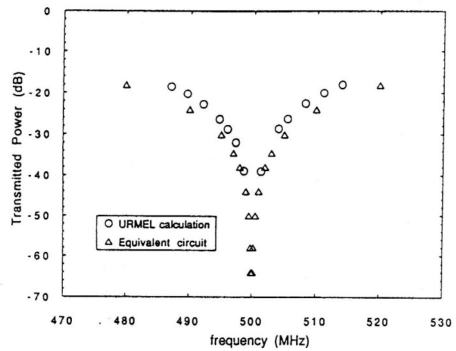


Figure 5. Frequency characteristics of the notch filter

Appendix 3/4

- High field cold test with 1/3 scale Niobium cavity with coax.
  - The coaxial pipe is attached.
  - MP appeared at very low field, probably at the coax. It was overcome by conditioning for 1 hour.
  - After the MP zone was passed, the field could be successfully raised over 1.83 MV kick voltage. It is above the design kick voltage of KEKB, 1.4 MV.
- 1/1 scale cavity with coax (Hosoyama-san).
  - Similar experience and performance was obtained.

K. Akai et al, 1993PAC

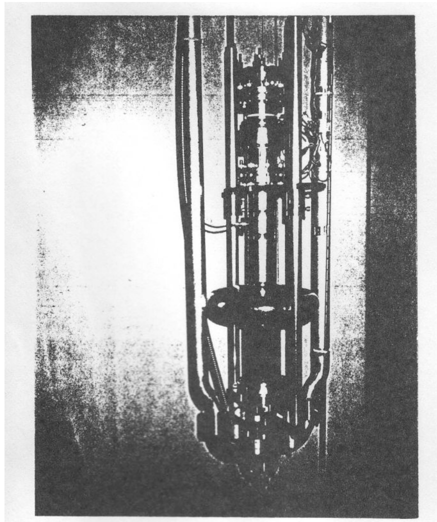


Figure 5. One-third scale niobium crab cavity with a notch filter and a coaxial beam pipe mounted on a test stand.

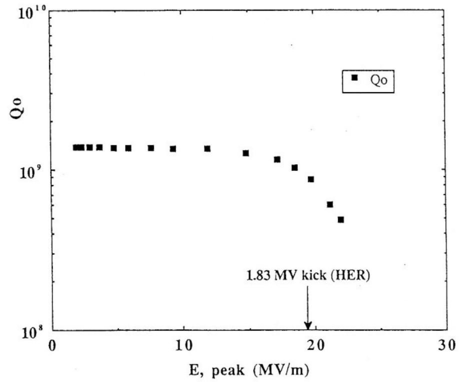


Figure 6. Surface peak field versus Q curve.

Summary of Appendix 4/4

- With the rejection of notch filter, a displacement of inner conductor of coax by +/- 3mm causes no significant problem.
- Field in the downstream of coax line and the notch filter is small, if the coax is well aligned.
- Preliminary cold test showed that MP at the inner conductor could be overcome by conditioning for one hour.