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CALIBRATION OF SRF CAVITY VOLTAGE BY MEASUREMENT OF SYNCHROTRON FREQUENCY IN SuperKEKB

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Abstract

Eight SRF cavity modules, which have been operated in KEKB for more than ten years, are stably operating also in SuperKEKB. As for calibration of the cavity voltage V_c, non-negligible discrepancy was observed between the results obtained from two different methods: one is using external Q value (Q_{ext}) of pickup ports, and the other is using loaded Q value (Q_L) of the cavities. The discrepancy comes from inaccuracy of power measurement in high power RF system and uncertainty of the Q_{ext} or Q_L values. In order to solve the discrepancy by improving the accuracy of the calibration for each individual cavity, we investigated a method by measuring synchrotron frequency f_s of stored beam. With this method, V_c calibration can be performed without affected by inaccuracy of high-power measurement or uncertainty of the Q_{ext} or Q_L values. The f_s measurement studies were carried out in SuperKEKB. With these studies, V_c calibration was obtained with a high accuracy of about 1%. The results are applied to the SuperKEKB operation.

INTRODUCTION

The SuperKEKB accelerator [1] is an electron-positron asymmetric energy collider that aims for a luminosity of 8×10^{35} /cm^2/s, which is 40 times higher than that of the KEKB accelerator. SuperKEKB main ring consists of a 7 GeV electron ring (high energy ring, HER) and a 4 GeV positron ring (low energy ring, LER). In order to achieve high luminosity, the stored beam currents are designed as 2.6 A for HER and 3.6 A for LER, which are twice those achieved in KEKB. After Phase-1 commissioning beam operation in 2016, the Belle II detector has been rolled in and the operation of the positron damping ring has started. Phase-2 operation started in 2018, and the first beam collision event was observed at Belle II in April [2, 3]. A full-scale collision experiment (Phase-3) started in March 2019 [4], and a peak luminosity of 2.96×10^{34} /cm^2/s was recorded in May 2021 with the beam currents of 680 mA for HER and 840 mA for LER.

The eight superconducting accelerating cavities (SCC) and eight normal-conducting accelerating cavities (ARES) [5] are operating in HER. The SCC is a higher-order-mode (HOM) damped cavity [6-9] developed for KEKB. Despite more than 20-years of usage, the SCC operation has maintained stable by keeping good performance with help of horizontal high pressure water cleaning [10, 11] and regular RF aging. The cavity voltage V_c of each SCC has been kept at 1.35 MV. The frequency of beam abort caused by cavities, so-called the trip rate, has been less than 0.1/day/eight cavities in recent operation.

An issue is related to calibration of V_c for each individual cavity with a sufficiently high accuracy. For SCCs, two independent methods are usually used: one is use of monitor power at the pickup port of cavity with the external Q value (Q_{ext}) of the pickup port. The other is use of cavity input power with the loaded Q value (Q_L) of cavity. In some cases, such as for some of the SCCs in SuperKEKB, non-negligible discrepancy is observed between the results obtained from the two methods. One reason is inaccuracy of power measurement in high power RF system. Another reason is uncertainty of the Q_{ext} or Q_L values. In order to improve the accuracy of the calibration, measurements using beams can give powerful information to correct these calibrations by eliminating inaccuracy of high-power measurement. In DESY, V_c calibration based on measurement of beam-induced voltage was performed [12]. In SuperKEKB, a different approach based on f_s measurement is investigated. A benefit of our approach is that the calibration is performed without affected by an error of Q_L. With this method, V_c calibration can be performed without affected by inaccuracy of high-power measurement or uncertainty of the Q_{ext} or Q_L values.

In this report, we will present the method of V_c calibration for each independent cavity using f_s measurement as well as results of studies of this method applied to SuperKEKB operation.

STATUS OF SCC IN SuperKEKB

A cross-sectional view of the SCC in SuperKEKB is shown in Fig. 1. It is a 509-MHz single-cell HOM damped cavity made of niobium. The HOM power is damped by a pair of ferrite absorbers [9] attached at beam pipes outside

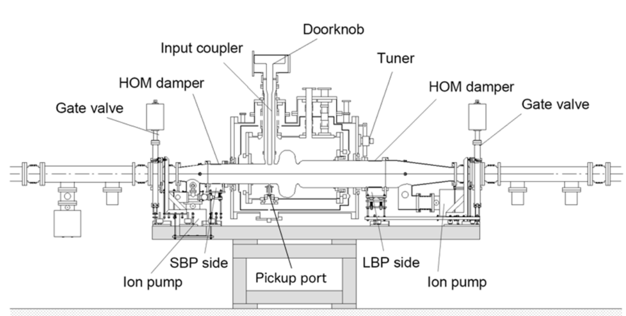

Figure 1: Cross-sectional view of the SCC module of SuperKEKB.

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of the cryostat. The RF power input coupler is a coaxial-type antenna. The cavity voltage is monitored by a pickup port of the cavity. Table 1 shows SCC-related parameters that are achieved in KEKB as well as those of SuperKEKB design values. The main issues are the large HOM power due to large beam current and cavity performance degradation during long-term operation.

Table 1: SCC-related Parameters in HER

Parameters	**KEKB (operation)**	**SuperKEKB (design)**
Energy [GeV]	8.0	7.0
Beam current [A]	1.4	2.6
Number of bunches	1585	2500
Bunch length [mm]	6	5
Number of SCC system	8	8
Total beam power [MW]	~5	8.0
Beam power [kW/cavity]	400	400
Total RF voltage [MV]	15.0	15.8
Cavity voltage [MV/cavity]	1.5	1.5
HOM power [kW/cavity]	16	37

HOM power in SuperKEKB becomes more than double that of the maximum value in KEKB [8] due to the higher beam current and shorter bunch length than those in KEKB. According to a simulation, 40% of the HOM power generated around one SCC is emitted through the ferrite damper and becomes additional load of the adjacent SCC [10]. To reduce the load of the next SCC, an additional HOM damper made of SiC has been installed for one cavity in 2017. It is confirmed that the HOM power absorbed by ferrite damper of the next SCC was successfully reduced around 20% after the SiC-damper installation [13]. As a countermeasure for the higher beam current operation, the SiC-damper will be installed for the rest of cavities.

The unloaded Q value, Q_0, of some of the SCCs degraded significantly at 2 MV with intense X-rays. The degradations are due to particle contamination in vacuum works of cavities in the long-term operation. To remove contaminants, we have developed a horizontal high pressure rinsing method (HHPR) [10, 11]. The HHPR was applied to three degraded SCCs. The Q_0 values were successfully recovered to 1×10^9 at 2 MV. They are operating stably in SuperKEKB beam operation.

To maintain the cavity performance, the RF aging in regular maintenance days scheduled every two weeks is also effective. The SCCs are warmed up and cooled down every beginning and ending of long shutdown in summer and winter. The warm-up process is effective to remove condensed residual gas on the cavity surfaces, although there is a risk of helium leakage by thermal cycle. The performances of almost all cavities are maintained with Q_0 higher than 1×10^9 at 1.5 MV and the maximum V_c higher than 2 MV by the HHPR and the regular RF aging.

V_C CALIBRATION BY f_S MEASUREMENT

V_c Calibration by Ordinal Methods Using Q_{ext} or Q_L

The cavity voltage V_c of SCC is defined as

$$|V_c| = \sqrt{R_{sh}P_c} = \sqrt{\frac{R}{Q}Q_0P_c} = \sqrt{\frac{R}{Q}Q_{ext}P_{pickup}}\,, \tag{1}$$

where R_{sh} is the shunt impedance of cavity, P_c the power loss in cavity, and P_{pickup} the monitored power at pickup port. Since the R/Q value and Q_{ext} are known, V_c can be obtained by P_{pickup} from Eq. 1. In the RF control system (LLRF), RF detectors are used to measure RF power. P_{pickup} is represented as

$$P_{pickup} = (A\times V_d^2)\times 10^{\frac{K_{loss}}{10}}, \tag{2}$$

where V_d is detector voltage, A is coefficient of RF detector and K_{loss} in dB is total power loss of cables and inside of control modules. Thus, V_c is obtained as

$$V_c = V_d\sqrt{A\times 10^{\frac{K_{loss}}{10}}}\sqrt{\frac{R}{Q}Q_{ext}}. \tag{3}$$

After the KEKB operation, K_{loss} was remeasured before starting SuperKEKB operation. On the other hand, Q_{ext} can only be measured in a vertical test of a cavity before assembling a cryomodule. Therefore, the Q_{ext} values measured in the construction period of KEKB more than 20 years ago are used. In the LLRF of SuperKEKB, the V_c obtained by Eq. 3 is used as a reference value of feedback control.

Since the coupling $\beta \gg 1$ in SCC, V_c is also calculated from Q_L and the input power to the cavity (P_{in}) with no storage beam as follows:

$$V_c = \sqrt{4P_{in}}\sqrt{\frac{R}{Q}Q_L}\,. \tag{4}$$

P_{in} is obtained from Eq. 2 similarly as the case of P_{pickup}. K_{loss} for P_{in} includes the coupling factor of a waveguide-type directional coupler, which is measured by manufacturer before shipment. Q_L is obtained from time constant of reflection power decay from the cavity measured at startup from long shutdown.

Discrepancy between the Two Methods

In several SCCs, there is a considerably large discrepancy between the V_c values calculated by the two methods, from P_{pickup} with Q_{ext} and P_{in} with Q_L. As an example of the discrepancies, for the cavity D11B with P_{in} = 50 kW, V_c calculated from P_{pickup} with Q_{ext} is 0.84 MV, whereas V_c calculated from P_{in} with Q_L is 0.92 MV. If the V_c from P_{in} with Q_L is correct, the actual V_c of this cavity is 10% higher, which means that the cavity is operating with a smaller margin than the other cavities.

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Possible causes of the discrepancy include inaccuracy of high-power RF measurement as well as uncertainty of the Q_{ext} or Q_L values. For the high-power RF measurement, typically a few % of the error should be taken into consideration. Also, the measured Q_L value has an error of a few %. In addition, the Q_{ext} of the pickup port may have changed for some reasons during long-term operation, although Q_{ext} cannot be remeasured.

New V_c Calibration Method by f_s Measurement

In order to obtain the V_c calibration factor of individual SCC with a higher accuracy, we investigated a V_c calibration method by measuring the synchrotron frequency f_s of the storage beam. This method can give more accurate V_c calibration factors, independent of the Q_{ext} or Q_L values. Also, it is not affected by the uncertainty of high-power RF measurement.

The f_s is represented as

$$2\pi f_s = \sqrt{\frac{\alpha f_{rev}}{E_0} eV_{c.tot} 2\pi f_{rf} \sin\phi_s} \tag{5}$$

$$\phi_s = \arccos\left(\frac{U_0}{eV_{c.tot}}\right) , \tag{6}$$

where α is the momentum compaction factor, f_{rev} the revolution frequency, E_0 the beam energy, $V_{c.tot}$ the total cavity voltage, f_{rf} the RF frequency, ϕ_s the synchronous phase, and U_0 the synchrotron radiation loss. The beam design parameters in SupeKEKB HER are shown in Table 2. E_0 has been checked by an energy scan, which confirmed the center of mass energy of the beam is on the Y(4s) resonance as designed [4]. $V_{c.tot}$ can be calculated from measured f_s using Eq. 5 and 6. The error to $V_{c.tot}$ comes from parasitic energy loss of the beam and deviation of α from the design value, which are estimated to be around 1–2% for each. To obtain more accurate V_c calibration factors, the estimation of the deviation of α is important, as will be described later.

Table 2: SuperKEKB HER Design Parameters

Parameters	SuperKEKB HER
E_0 [GeV]	7.007
Circumference [m]	3016.31
f_{rev} [kHz]	99.39
f_{rf} [MHz]	508.88
α	4.54×10^{-4}
U_0 [MeV]	2.43

Figure 2 shows the relation between V_c setting of SCC and synchronous phase ϕ_s, where V_0=U_0/e. First, the *Base*V_c is set by four base cavities and the other four cavities (target cavities) are parked. With this condition, the measured f_s is $f_{s.base}$. Next, the $V_{c.tot}$ is set by one of the target cavities (*Trgt*V_c) added to the *Base*V_c. In order to make the ratio of *Trgt*V_c to *Base*V_c as large as possible, the *Base*V_c and *Trgt*V_c are chosen as 6 MV (4×1.5 MV) and 1.8 MV, respectively. The maximum f_s ($f_{s.max}$) and minimum f_s ($f_{s.min}$) are measured by searching RF phase scan of the target cavity more than 180 degrees. This procedure is repeated for the other three target cavities one-by-one.

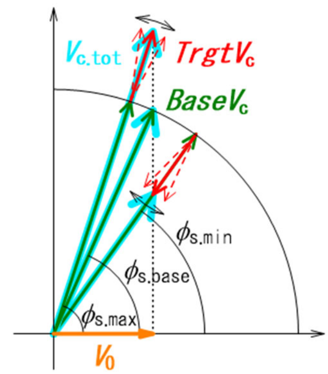

Figure 2: Schematic view of V_c calibration method by measurement of f_s. *Base*V_c is vector sum of four base cavities. The *Trgt*V_c is the cavity voltage of a target cavity of the calibration. $V_{c.tot}$ is vector sum of *Base*V_c and *Trgt*V_c.

In addition to the high *Trgt*V_c, the measurement accuracy is much improved by using both $f_{s.max}$ and $f_{s.min}$, compared to using only $f_{s.max}$. With these conditions, calculated values of ϕ_s and f_s with no error in each cavity voltage are shown in Table 3.

Table 3: V_c Settings and Calculated Values of ϕ_s and f_s

Parameters	Set V_c [MV]	Set $V_{c.tot}$ [MV]	Calc. ϕ_s [deg.]	Calc. f_s [kHz]
BaseV_c (base cavities)	6.0	6.0	66.1 ($\phi_{s.base}$)	1.69 ($f_{s.base}$)
+ *Trgt*V_c (on accel. phase)	1.8	7.8	71.8 ($\phi_{s.max}$)	1.97 ($f_{s.max}$)
- *Trgt*V_c (rot. 180 deg.)	1.8	4.2	54.6 ($\phi_{s.min}$)	1.34 ($f_{s.min}$)

It should be noted that the relative phase between the base cavities should be adjusted in-phase with a sufficiently high accuracy in advance: otherwise *Base*V_c (amplitude of vector sum) will be different from a scalar sum of V_c of individual four cavities. In daily operation, the relative phase in the eight SCCs is adjusted based on beam-loading change as a function of beam current. So, the relative phase is well adjusted with an accuracy of typically less than ±2 degrees. Thus, the difference of *Base*V_c and the sum of four cavities is negligibly small, less than 0.1%.

The f_s measurement studies were carried out in SuperKEKB beam operation twice in 2019 [14]. The eight SCCs were divided into two groups: Group A, which consists of D10B, D10D, D11A and D11B, and Group B which consists of D10A, D10C, D11C and D11D. All ARES cavities were parked with RF OFF. The measurement of f_s was performed with a single bunch of 0.5 mA, which makes the effects of beam-loading or coupled-bunch negligibly small. f_s is measured by FFT analysis of the bunch phase in a bunch-by-bunch feedback system [15]. The bunch current is kept constant as much as possible to reduce the effect of parasitic loss. In the 1st study, each of

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the four cavities in Group A was set as a target cavity and cavities in Group B were set as the base cavities. The 2nd study was carried out two weeks after the 1st study, and the setting of the target and base cavities was opposite of the 1st study.

An example of measured $f_{s.max}$ and $f_{s.min}$ is shown in Fig. 3 for one cavity, D11B. The horizontal axis is a scale of trombone-type phase shifter. Converted values to phase in degrees are also shown in top. The fluctuation of f_s values was around ±1 Hz in the measurement. The $f_{s.max}$ and $f_{s.min}$ were determined from the fit results. The measured f_s and the obtained calibration factors for the D11B and the base cavities are shown in Table 4. Here, the design value of α is used.

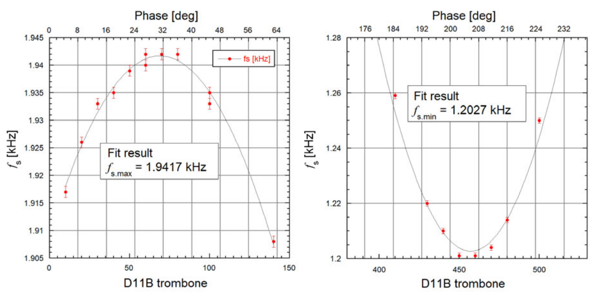

Figure 3: Example of measured f_s as a function of scale of trombone-type phase shifter of the target cavity. $f_{s.max}$ and $f_{s.min}$ from the fit results are also shown.

Table 4: Measured f_s and Obtained V_c Calibration Factors

Parameters	f_s [kHz]	$V_{c.tot}$ [MV]	V_c [MV]	Calib. Factor
Base V_c (base cavities)	1.632 ($f_{s.base}$)	5.657	-	0.943
+ *Trgt* V_c (on accel. phase)	1.942 ($f_{s.max}$)	7.625	1.97	1.094
- *Trgt* V_c (rot. 180 deg.)	1.203 ($f_{s.min}$)	3.688		

The V_c calibration factors of other seven cavities were obtained in the same manner. These calibration factors were applied to the operation after 2019 summer shutdown.

Evaluation of α

The α may be deviated from the design value by a few percent. Therefore, the actual value of α at the time of calibration study should be known to get the V_c calibration factor more accurately. However, it is difficult to determine the α with an accuracy of 1% from the measurement of beam optics. Therefore, during the 2021 spring run, we estimated the deviation of α using the data obtained in the studies as follows.

We focus on the calibration factors for the two groups, named K_A and K_B in Group A and Group B, respectively. For the group of base cavities, the calibration factors for the base cavities are used for K_i (i=A, B). For the group of target cavities, an average of the calibration factors is used. The ratio of K_B to K_A must be about the same values in the 1st and 2nd studies, since no big change of cavity performance is expected during the two weeks between the 1st and 2nd studies. On the other hand, the α can be different between these studies since beam optics correction was performed between the 1st and 2nd studies. So, the deviation of α is defined as correction factors $k_{\alpha 1}$ and $k_{\alpha 2}$ for the two studies, respectively. Table 5 shows K_A, K_B and the ratio (K_B/K_A) for the cases $k_{\alpha 1}$ or $k_{\alpha 2}$ of 0.97, 1.00 and 1.03. The factors in parentheses are averaged values for four target cavities. Figure 4 shows the ratio K_B/K_A as a function of $k_{\alpha 1}$ or $k_{\alpha 2}$. From the linear fit results, the relation between $k_{\alpha 1}$ and $k_{\alpha 2}$, which gives the same K_B/K_A in the 1st and 2nd studies, can be expressed as

$$k_{\alpha 1} + 0.98731 k_{\alpha 2} = 2.02917. \quad (7)$$

Table 5: Calibration Factors of Group A (K_A), Group B (K_B) and Ratio of K_B to K_A

k_α	Study #	Group A K_A	Group B K_B	K_B/K_A
$k_{\alpha 1}$=0.97	1st	(0.997)	0.967	0.969
$k_{\alpha 2}$=0.97	2nd	0.972	(0.982)	1.010
$k_{\alpha 1}$=1.00	1st	(0.961)	0.943	0.981
$k_{\alpha 2}$=1.00	2nd	0.949	(0.947)	0.998
$k_{\alpha 1}$=1.03	1st	(0.927)	0.920	0.993
$k_{\alpha 2}$=1.03	2nd	0.926	(0.913)	0.986

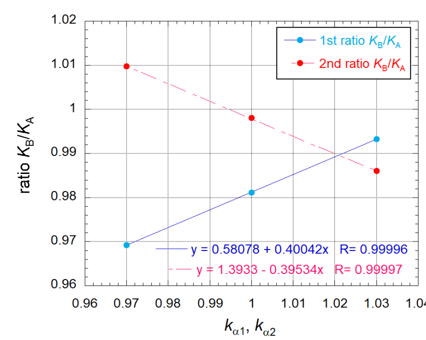

Figure 4: Ratio of the calibration factors of Group B (K_B) to Group A (K_A) as a function of $k_{\alpha 1}$ or $k_{\alpha 2}$. Linear fit results as a function of $k_{\alpha 1}$ or $k_{\alpha 2}$ are also shown.

Table 6: Additional f_s Measurement to Evaluate α

#	Set $V_{c.tot}$ [MV]	f_s [kHz]	Cavities	$\left\{ f_{s(meas)} / f_{s(cal)} \right\}^2$
1	4.5	1.4013	Group B–D11D	0.99393
2	6.0	1.683	Group A	0.98959
3	4.5	1.3983	Group A–D10B	0.98968
4	4.5	1.3953	Group A–D10D	0.98544
5	4.5	1.4013	Group A–D11A	0.99393
6	4.5	1.4030	Group A–D11B	0.99634

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Table 7: Summary of Calibration Factors Obtained from the f_s Measurement Studies

Cavity ID	D10A	D10B	D10C	D10D	D11A	D11B	D11C	D11D	D11D*
Calibration Factor in 2021**	0.955	0.889	0.974	0.923	0.873	1.067	0.857	0.911	0.920
Factors in 2019 Study [14]	0.977	0.910	0.998	0.946	0.894	1.094	0.878	0.934	-

D11D*: newly installed cavity to replace D11D
**: Correction of α by 2% is applied to the factors obtained in 2019.

To further determine $k_{\alpha 1}$ and $k_{\alpha 2}$, we checked if $k_{\alpha 1}$ and $k_{\alpha 2}$ are about the same values or not. For this purpose, an additional study was carried out. In this study, f_s measurements with various combinations of cavities, to which the V_c calibration factors have been already applied, were performed. In Table 6, the set value of $V_{c.tot}$, the measured f_s ($f_{s(meas)}$), used SCCs and the squares of the ratio of $f_{s(meas)}$ to the calculated f_s ($f_{s(cal)}$) are listed. (The D11D was replaced before this study, as described later.) The $\{f_{s(meas)}/f_{s(cal)}\}^2$ value means the product of the correction of α and the correction of $V_{c.tot} \sin\phi_s$. By comparing #1 (Group B) and the others (Group A), there is no considerable difference in the values of $\{f_{s(meas)}/f_{s(cal)}\}^2$. Therefore, the values of $k_{\alpha 1}$ and $k_{\alpha 2}$ are almost the same. Thus, it is concluded from Eq. 7 that $k_{\alpha 1} = k_{\alpha 2} = 1.02$. Consequently, the actual V_c for the eight SCCs have been around 2% lower than the V_c calibrated in 2019 described above. Then the V_c calibration factors in the 1st and 2nd studies were re-calculated with $k_\alpha = 1.02$.

Vc Calibration for Newly Installed Cavity

In Jan. 2021, the D11D cavity was replaced with one of the HHPRed SCCs. The V_c calibration study was carried out in this spring run to obtain the V_c calibration factor of the newly installed cavity (D11D*). k_α at the time of this study is obtained with the *Base*V_c using the re-calculated V_c calibration factors as above with measured f_s. The result of k_α is 1.02, which is about the same as that in the 2019 studies. The V_c calibration factor of the new D11D was obtained to be 0.920.

SUMMARY

The SCC system of SuperKEKB has been operating stably. In order to solve the non-negligible discrepancy in the V_c calibration between the two methods using Q_{ext} or Q_L, a new calibration method based on f_s measurement is investigated. Studies on this calibration were performed in 2019 and 2021. From these studies, the V_c calibration factors were obtained with an accuracy of about 1%, independent of Q_{ext} or Q_L. Table 7 shows a summary of the V_c calibration factors obtained from these studies. These new calibration factors will be applied from the fall 2021 operation.

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