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LOADING TEST OF HOM DAMPERS FOR SUPERCONDUCTING CAVITIES FOR HIGH CURRENT AT SuperKEKB

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Abstract

The design storage current of the electron ring for SuperKEKB is 2.6A which is around twice KEKB achievement. The HOM power of the superconducting cavity is estimated to increase over 35 kW from 14 kW, that is the achievement value at KEKB. The large load is unacceptable for the ferrite HOM dampers mounted on both sides of the cavity. As a countermeasure, the duct-type SiC HOM dampers are installed between the cavities. The load of the downstream ferrite HOM damper decreased because the HOM power is absorbed by the upstream SiC damper. The filling pattern of the beam affects the HOM power. The dependence is caused by the build-up factor of trapped mode that propagates to the LBP side.

INTRODUCTION

SuperKEKB is an energy asymmetric electron-positron collider for the particle physics [1]. SuperKEKB consists of two rings for positron and electron, named as low energy ring (LER) and high energy ring (HER), respectively. Superconducting cavities installed in HER. The design beam currents for LER and HER are 3.6 A and 2.6 A, which are over twice KEKB the typical operating current of 1.6 A and 1.2 A, respectively [2]. The main purpose of accelerator ring for particle physics is to push up the luminosity. SuperKEKB adopts the nano-beam scheme and very high current storage beam towards the goal. The luminosity archived the highest value of 4.65×10^{34} in June 2022 [3, 4]. SuperKEKB continues to be upgraded and increase beam current to design value.

The loading power by beam is proportional to the loss factor, beam current, and bunch charge. Bunch charge is not changed from KEKB. On the other hand, the loss factor and beam current are higher than KEKB. The design bunch length of SuperKEKB is 5 mm, which is shorter than KEKB operation value of 6 mm [1, 5]. The expected loading higher order mode (HOM) power at SuperKEKB design parameter of 37 kW is over twice of achieved value at KEKB era [1]. This power consumption is as the heat of the HOM damper. Additional power absorbers are installed between the cavities to address this enormous load.

This study shows the two experiments. The first confirms the validity of the SiC damper located between the cavities to increase the beam current [6–9]. The second result shows the fill pattern dependence of HOM power evaluated using an equivalent loss factor.

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SUPERCONDUCTING RF CAVITIES AT SuperKEKB

HOM Damped Cavity for SuperKEKB

Electron in HER is accelerated by eight superconducting cavities, and eight ARES cavities that are normal conducting cavities [1, 5]. The superconducting cavity was designed for KEKB, which is the previous high current accelerator project of SuperKEKB. The cavity parameters are shown in Table 1 [10, 11].

Table 1: Superconducting cavity parameters of SuperKEKB. RF Parameters not specified are those for TM010 mode.

Parameters	Unit	Value
Cavity type		single-cell
Material		Niobium (RRR)
Operating temp. (LHe)	K	4.4
Frequency	MHz	508.9
Gap length	mm	243
R_{sh}/Q_0		93
Geometrycal factor		251
E_{sp}/E_{acc}		1.84
H_{sp}/E_{acc}	mT/MV/m	4.03
Q_0 at 1.5 MV (6.2 MV/m)		$> 1 \times 10^9$
Operating Q_L $\simeq Q_{ext}$ of input coupler		$5.3 - 7.7 \times 10^4$

This cavity focuses on the damping HOM caused by a high beam current and small beam size. Beam pipes of different large diameters are attached to the ends of the cavity and are called a small beam pipe (SBP) and a large beam pipe (LBP), respectively. SBP diameter is 220 mm, the same as the iris diameter of the cavity to propagate the parasitic monopole mode [10]. The diameter of the LBP is 300 mm to propagate the lowest parasitic dipole mode. The propagated HOMs are absorbed by the ferrite damper located outside the cryostat [11, 12]. Feature of superconducting HOM damped cavity at KEKB have already been explained in many past papers such as [7, 10, 11, 13–15].

SiC HOM Damper

Superconducting cavities are located at one straight section of the HER named the Nikko section. Figure 1 shows the layout of the cavities and the additional SiC HOM damper between the cavities [6, 8, 9]. Currently, two additional SiC HOM dampers have been installed to ring.

The cut-off frequencies of 150 mm diameter beam pipe are 1.17 GHz and 1.53 GHz for TE11 mode and TM01 mode, respectively. Therefore, if the frequency of HOM power is

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higher than the cut-off frequency, the power can propagate through the beam pipe. This HOM is absorbed in the downstream HOM damper. This energy propagation imposes a large additional load of HOM dampers. To reduce the load of the downstream HOM dampers, the additional SiC HOM damper install and perform test toward the increase beam current.

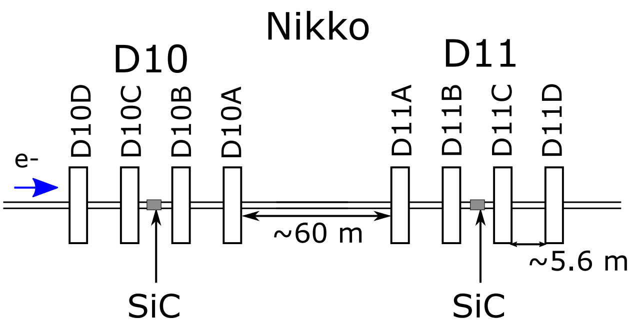

Figure 1: Cavities and SiC HOM damper layout at Nikko section of SuperKEKB. The cavities are named from D10D at the most upstream of D11D in order. The distance between each cavity is around 5.6 m. The straight section is separated by two sides to the left and right by around 60 m. SiC damper has been installed downstream of D10C in 2018 and D11B in 2021.

EVALUATION OF HOM LOADING

Equivalent Loss Factor

We defined the equivalent loss factor (Eq. LF) k_{eq} as the distributed total loss factor k to each component [6, 15]. The beams lose energy due to emission of the electric magnetic field depending on the impedance of components. The beam loss power P is described as

$$P_{\mathrm{b}} = kqI_{\mathrm{b}}, \tag{1}$$

$$k = \sum_{\mathrm{a}} k_{\mathrm{eq,a}} \tag{2}$$

$$k_{\mathrm{eq,a}} := \frac{P_{\mathrm{a}}}{P}, \tag{3}$$

where, q is charge of the bunch, I_{b} is the average beam current, k is loss factor. This power can be represented by superposition of the power dissipation at each component as P_a. The subscript ”a” is the distinction of the component that dissipates or propagates power. The $k_{\mathrm{eq},a}$ is defined as the ratio of partial power loss to total power loss. The $k_{\mathrm{eq},a}$ has the same unit of V/pC as loss factor k. The Eq. loss factor can evaluate the dissipation and propagate power at local components like the HOM damper and through the beam pipe. Conventionally, the loss factor can calculate by the computing code. The Eq. LF can be compared to the actual measurement loading and calculation result of the energy flow independent of the charge and the beam current.

Absorption Power Measurement

The HOM power absorbed by the HOM damper is evaluated using the temperature difference between the cooling water inlet and outlet and the flow rate. The temperature of the cooling water fluctuates as a result of the refrigeration cycle by the water chiller. Therefore, the temperature rise caused by HOM power absorption is evaluated using the average temperature to ignore the time fluctuation. The typical absorption power P is defined by the typical heat load per unit of time, as shown in follows

$$P = \overline{Q}, \tag{4}$$

$$Q = \rho c \Delta T f_{\mathrm{w}}, \tag{5}$$

where, ρ is the density of water, c is the specific heat capacity, ΔT is the increase in temperature, f_{w} is the volumetric flow rate of water.

BEAM TEST RESULT

Reducing Downstream Loading by SiC HOM Damper

Evaluation of the SiC HOM dampers installed to the ring is ongoing under the usual beam operation. Figure 2 shows the absorption power by dampers in D11 in 2018 and 2022 operation. Conventionally, the total of the absorbed power of the ferrite dampers at SBP and LBP is assessed for each cavity HOM power. In Fig. 2 (a), the absorbed power of each ferrite damper at SBP and LBP is plotted as separate points to confirm the effect of load reduction by the SiC damper on the downstream load of the ferrite dampers. However, the absorption power depends on the operation conditions such as beam current and number of bunches. Therefore, the Fig. 2 (b) shows absorption power normalized by the absorbed power of the ferrite HOM damper at the most upstream. The absorption power of the ferrite HOM damper downstream of the SiC HOM damper decreased due to the SiC HOM damper.

Evaluation of Eq. LF of HOM Dampers

The Eq. LF can be obtained using the absorption power, bunch charge, and average current of ring as follows:

$$k_{\mathrm{eq}} = \frac{P_{\mathrm{abs.}}}{\frac{I_{\mathrm{b}}}{N_{\mathrm{b}} f_{\mathrm{rev}}} I_{\mathrm{b}}}, \tag{6}$$

where, $P_{\mathrm{abs.}}$ is absorbed power that evaluated using cooling water temperature and volumetric flow rate, N_{b} is number of bunches, f_{rev} is revolution frequency, and $I_{\mathrm{b}}/N_{\mathrm{b}} f_{\mathrm{rev}}$ is average bunch charge.

In operation during 2022 of SuperKEKB, total beam currents increased from around 800 mA to over 1 A of HER [4]. To achieve the high current, the beam filling pattern was changed. The bunch spacing is selected by the combination of 4 ns spacing and 6 ns spacing corresponding to 2-bucket and 3-bucket, respectively.

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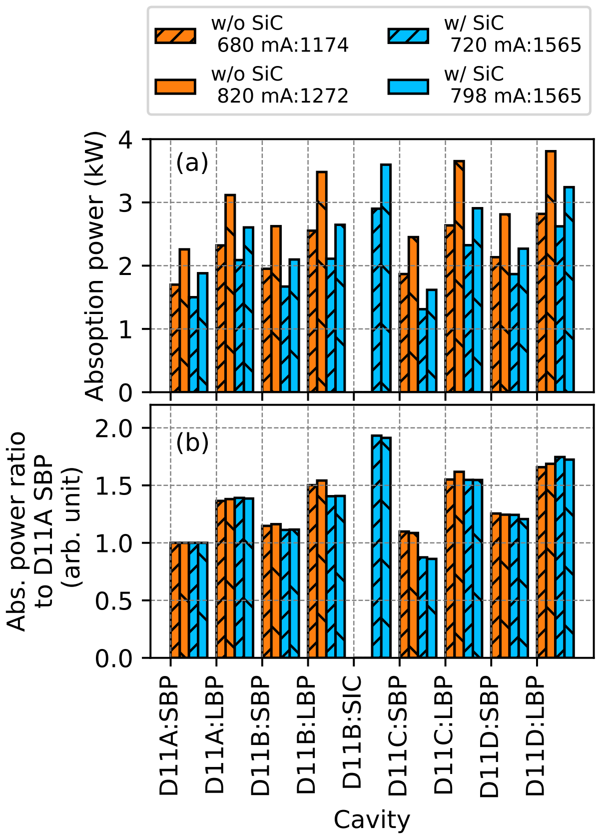

Figure 2: The absorbed power of HOM dampers under some operation in SuperKEKB. Blue bar shows the actual value before installing SiC HOM damper at 2021b operation. Orange bar shows the actual value after installing SiC HOM damper at 2022ab operation. Figure (a) is the absolute absorption power for each HOM damper. Figure (b) is the ratio of the absorption power to the most upstream damper of D11A SBP side.

Figure 3 shows the relation of measured Eq. LF and bunch current that defined as I_b/N_b. The Eq. LFs of the ferrite HOM damper at SBP of each cavity and SiC HOM dampers slightly depend on the bunch current, contrary to the definition. This dependence of the bunch current could be attributed to the difference of the bunch length.

Figure 4 shows the relation of the measured Eq. LF and bunch number. The Eq. LF of the ferrite HOM damper at SBPs of each cavity and SiC HOM dampers is independent of bunch number. On the other hand, Eq. LF of the ferrite HOM dampers at LBP side of cavities increased with bunch number. Scattering of Eq. LF of the ferrite damper at LBP also appears in Fig. 3 This difference implies the induced HOM mode difference. The cut-off frequency of LBP beam pipe is 765 MHz for TM mode and 585 MHz for TE mode. Likewise, the cut-off frequency of the SBP beam pipe is 1.04 GHz for TM mode and 798 MHz for TE mode. Table 2 shows the list of major TM mode HOM and loss factor.

The loss factor at 1018 MHz mode is relatively high because R_{sh}/Q_0 is relatively high. Hence, a ferrite HOM

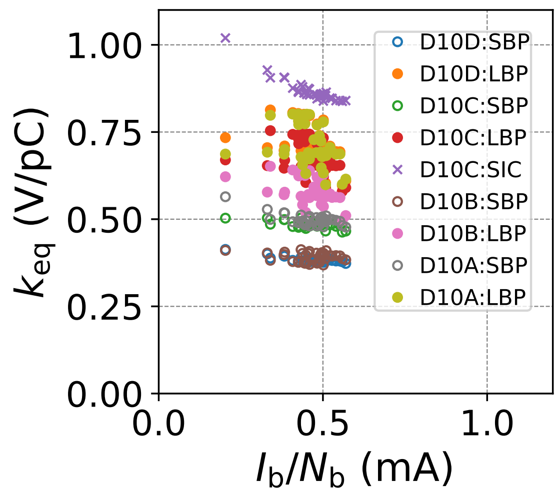

Figure 3: Measured k_{eq} of each HOM damper relate to the bunch current I_b/N_b.

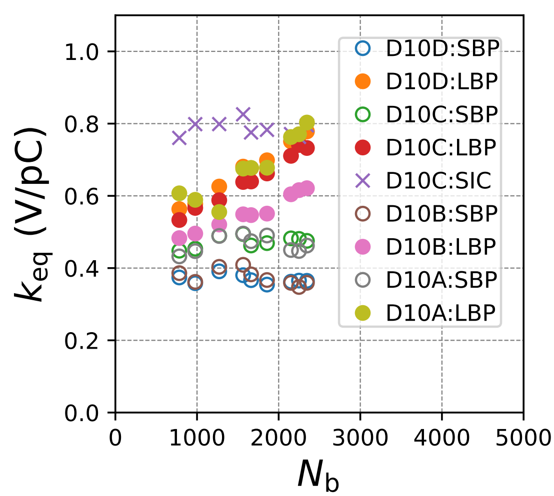

Figure 4: Measured k_{eq} of each HOM damper relate to the bunch number N_b.

Table 2: List of major TM mode HOM that has lower than cut-off frequency of LBP, frequency, loss factor, $|F|$ for 2-3 bunch spacing (BS). This assumption bunch fill all bucket and exclude the bunch gap. Parameters of HOMs to calculation ware used from Ref. [16].

Freq. (MHz)	k_a	$\|F\|$ (2 BS)	$\|F\|$ (3 BS)
TM			
782	0.00036	2.0	0.19
834	0.00042	0.42	1.8
918	0.0017	0.18	0.15
1002	0.0090	2.0	1.4
1018	0.019	13.5	9.0
1032	0.0024	1.1	0.81
1065	0.0021	0.76	0.42

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damper at LBP absorbs the HOM power more than a ferrite HOM damper at SBP as the cavity design. This character is shown in Figs. 2, 3, and 4.

Beside, if the decay time of the exited HOM is longer than the bunch spacing T_b, HOM will build up. The bunch train fills the loading RF power by summation of single bunch induced voltage with the ratio τ of T_b between bunches to the decay time and the phase rotation that is defined by $\delta = (\omega_a - \omega_{rf})T_b$. Where, ω_{rf} is fundamental rf frequency is proportional to revolution frequency. Then, this convergence can be expressed using single bunch beam-induced voltage and the function of τ and δ [17]. The build-up function was defined by the convergent that normalized by single bunch induced voltage as

$$V_b = \sum_{n,a} V_{b0,a} e^{(-\tau_a + i\delta_a)n} \tag{7}$$

$$= \sum_{a} V_{b0,a} F(\tau_a, \delta_a), \tag{8}$$

where, subscript a distinguish HOM mode. The function F is complex function and the real part is the coupling the beam. The HOM that exited in the cavities is complex field. Therefore, the power from HOM is depend on absolute value of complex voltage. Absorption power corresponds to

$$P_a = \frac{V_{b,a}^2}{\frac{R_{sh}}{Q_0}_a Q_{0,a}}. \tag{9}$$

For the HOM in Table 2, HOMs at 1018 MHz has a large value of function $F(\tau_a, \delta_a)$ compared to other modes by a few order. The power ratio of 2-bucket to 3-bucket at 1018 MHz HOM is around 1.3 times at the same total current, which means the different bunch current. The operating by bunch number of 1565 and 2346 almost correspond to 3-bucket and 2-bucket condition.

This simple consideration qualitatively explains the scattering of k_{eq} of the ferrite HOM damper at LBP. The ferrite HOM damper at SBP and SiC HOM damper is independent of these HOM because frequencies are lower than cut-off of these.

SUMMARY

SuperKEKB continues to bush up the luminosity. An increase in the HOM power with an increase in the storage current is a concern for the SRF. Two duct-type SiC HOM dampers have been installed between the cavities to reduce the propagation HOM to the downstream. HOM reduction effect was confirmed during operation. The heat load of the ferrite HOM damper is necessary to be reduced to counteract the further current increase. On the other hand, HOM power depends on the bunch number, which qualitatively explains that the HOM of the trapped mode in LBP is strongly affected by the bunch interval. We will conduct an HOM power estimation, include bunch gap and fine structure of cavities, and install the additional SiC HOM dampers in order to increase the current in the future.

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