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HIGHER ORDER MODE POWER IN SUPERCONDUCTING CAVITIES OF SUPERKEKB WITH HIGH CURRENT OPERATION

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Abstract

SuperKEKB is a high-current accelerator machine for high-luminosity. Higher order mode (HOM) damped single-cell superconducting cavities accelerated an electron beam in the main ring since KEKB. the number of bunches was observed in 2022 operation. One of the reasons for this is thought to be a build-up effect of some parts of the HOM caused by narrow bunch spacing. It was found in the last operation that this problem has an individual difference for each cavity. As the accelerator is expected to reach its design current in the future, the HOM power will also increase and ferrite HOM dampers will have to cope with the increasing HOM power resulting from the build-up. This report provides an overview of the status of the superconducting cavity HOMs last operation in 2023-2024.

INTRODUCTION

SuperKEKB is an asymmetric energy electron positron collider designed to produce a lots of B-mesons, serving as a high-luminosity accelerator for the Belle II experiment [1]. Compared to previous machine KEKB, SuperKEKB is designed to operate with beam currents of 3.6 A in the Low Energy Ring (LER) for positrons and 2.6 A in the High Energy Ring (HER) for electrons. To accelerate these high-current beams, two types of RF accelerating cavities are operating. The ARES cavity, which is a normal-conducting cavity, and a superconducting cavity. Among these, the superconducting cavities are installed only in the HER. Currently, SuperKEKB is steadily increasing its stored beam current toward its target luminosity. The superconducting cavities are required to operate stably in order to support this ambitious SuperKEKB project [2].

SuperKEKB Operation

During the long shutdown period known as LS1, which began in the summer of 2022, several upgrades were implemented at SuperKEKB, including the installation of nonlinear collimators in the LER. As a result, the goal for 2024 operation was to achieve higher stored beam currents than in previous SuperKEKB runs [3]. Indeed, by the spring run of 2024, the stored current in HER exceeded 1.1 A. After summer maintenance at 2024, further high-current operation was carried out in the winter run at 2024, reaching 1.7 A in the LER and up to 1.3 A in the HER. In addition to beam current, the primary aim of the accelerator, the luminosity, also surpassed the previous world record during this period.

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HOM DAMPED SUPERCONDUCTING CAVITY

Cavity Design

The design of the superconducting cavities used at SuperKEKB is based on those originally developed for the KEKB accelerator [4].

One of the most notable features is its ability to deliver up to approximately 400 kW of RF power to the beam, with stable operation already demonstrated at 350 kW. To support ampere class beam operation, special attention was given to the suppression and extraction of HOMs.

To extract HOMs efficiently, the cavity is equipped with beam pipes of different diameters at each end referred to as the Large Beam Pipe (LBP) and the Small Beam Pipe (SBP). These allow HOMs to propagate out of the cavity, where they are subsequently absorbed by HOM dampers. Despite the substantial increase in beam current from KEKB to SuperKEKB, the existing superconducting cavity will be providing the required beam power without significant modification. Therefore, the same cavity continue to be used at SuperKEKB. Detailed performance results from recent operation can be shown in [5].

HOM Damper

The HOM dampers are cylindrical ferrite absorbers installed at the room-temperature sections located downstream of both SBP and LBP [6–8]. To suppress the HOM power generated in the cavity, these ferrite absorbers reduce the quality factor Q of HOMs to below 200 [9]. At the design beam current of SuperKEKB, the total HOM power is estimated to reach around 37 kW more than twice the maximum absorbed HOM power during the KEKB era. Accordingly, it is essential to effectively absorb the substantial HOM power generated in the superconducting cavities of SuperKEKB. Although beam instabilities such as coupled-bunch instabilities are expected to remain below threshold under SuperKEKB operating conditions, the temperature rise due to power dissipation in the absorber itself has raised concerns about potential cracking or damage. Simulations have shown that a majority of the 37 kW of HOM power resides in high frequency components, which propagate downstream through the beam pipe. In response, SuperKEKB has adopted a mitigation strategy that involves installing additional HOM dampers between cavities to intercept and absorb the propagating HOMs [10–12]. These newly introduced HOM dampers use SiC as the absorber material. As the beam current increases step by step, more SiC dampers

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are being added for future. Two SiC HOM dampers have been installed at present. The load of the downstream ferrite HOM dampers in the superconducting cavities effectively reduced [13].

Loss Factor

A detailed cavity model was constructed and used to recalculate the loss factor using CST. The model incorporates the drawing cavity dimensions, with the metallic surfaces treated as perfect electric conductors (PEC) and the dampers modeled with lossy materials. The calculations were performed using the wakefield solver. The relationship between the loss factor and the bunch length is shown in Fig.1.

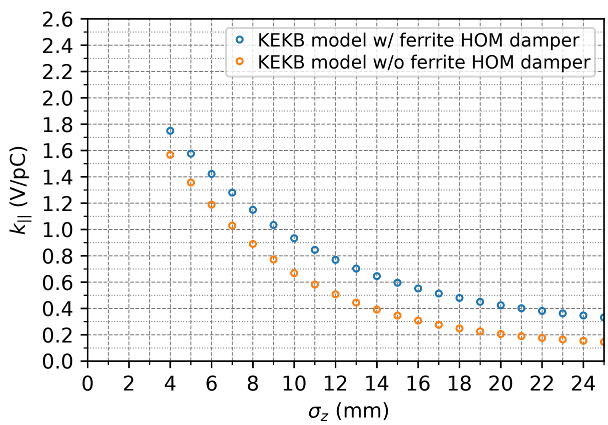

Figure 1: Loss factor as a function of bunch length calculated using the CST Studio Suite wakefield solver. The simulation was performed using a detailed model of the KEKB superconducting cavity. A comparison is cavity with and without the ferrite HOM damper.

The design bunch length is 5 mm of SuperKEKB. The total loss factor of the superconducting cavity is around 1.7 V/pC. We used loss factor values from rough model were used in [11, 12]. However, as precise prediction of the high HOM power has become increasingly important, this newly calculated value will be adopted for future HOM power estimations.

Eq. Loss Factor

To estimate the heat load absorbed by each HOM damper, a parameter called the *equivalent loss factor* (k_{eq}) is used [13,14]. This value is evaluated in simulations by calculating the ratio of the magnitudes of the Poynting vectors passing through each component. For convenience, k_{eq} is converted to a value per bunch charge, similarly to the conventional loss factor, and is defined as

$$k_{eq} = \frac{P_{abs.}}{\frac{I_b}{N_b f_{rev}} I_b}. \tag{1}$$

where $P_{abs.}$ is the absorbed power, I_b is the total beam current, N_b is the number of bunches, and $f_{rev} = 99.6$ kHz is the revolution frequency [13].

This parameter corresponds exactly to the slope of the plot where the horizontal axis is the beam current $\frac{I_b}{N_b f_{rev}} I_b$ and the vertical axis is the absorbed power.

HOM LOAD RESULT

The power absorbed by the HOM absorbers is determined from the temperature rise of the cooling water in the HOM dampers. The temperature increase of the cooling water is defined as ΔT, the volumetric flow rate is f_w, the specific heat capacity of water is c, and the density is ρ. Then, the heat absorbed by the HOM damper, Q, is given by

$$Q = c\rho\Delta T f_w. \tag{2}$$

Since the cooling water flow rate is controlled and remains approximately constant, the absorbed heat Q can be considered proportional to the temperature difference ΔT. However, as the water temperature is regulated by a chiller, periodic temperature fluctuations associated with the chiller controller. Therefore, ΔT is evaluated as an average over more than three hours. The uncertainty is estimated using the maximum and minimum temperature variations observed in the cooling water since 2022. SuperKEKB began beam operation in 2016 and has steadily increased the beam current since then. Accordingly, the absorbed HOM power in the dampers has also increased. Figure 2 shows the trend of the main HOM power measurements to date.

HOM Build Up Problem

During past operations, it has been observed that the power absorbed by the HOM dampers is affected not only by the beam current but also by the bunch spacing [13]. Although the harmonic number of SuperKEKB is 5120, not all buckets are filled in order to suppress beam instabilities. Additionally, two abort gaps and the nominal number of bunches is set to 2346. In this filling pattern, the bunch spacing corresponds to a 2-bucket spacing. Following the procedure in [6,15], the buildup factor under this condition is calculated as

$$V_b = \sum_a V_{b0,a} F(\tau_a, \delta_a), \tag{3}$$

$$F(\tau,\delta) = \frac{1-e^{-2\tau}}{2(1-2e^{-\tau}\cos\delta + e^{-2\tau})} + i\frac{2e^{-2\tau}\sin\delta}{2(1-2e^{-\tau}\cos\delta+e^{-2\tau})}. \tag{4}$$

As a result, the HOM accumulation rate in the cavity changes, leading to a change in the heat load absorbed by the HOM dampers. In particular, the KEKB superconducting cavity has a TM_{011} mode at 1018 MHz, which is quite close to the beam frequency spectrum. Although the Q_0 value of this mode is significantly suppressed by the HOM dampers, the HOM buildup causes the absorbed power to increase by about 1.3 times compared to the previous 3-bucket spacing operation. Consequently, the actual HOM power that needs to be absorbed may exceed the previously predicted 37 kW.

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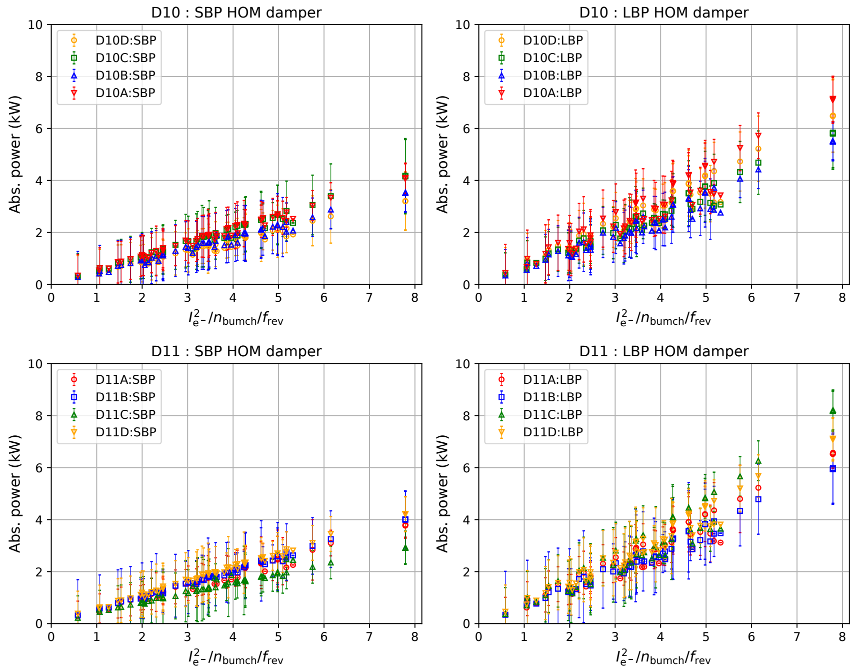

Figure 2: HOM absorption power of each HOM damper from 2016 to 2024 winter run. Only data from the stable operation lasting more than three hours are used. The error bars represent the range between the maximum and minimum water temperature variations and include all available data from 2022 to 2024.

Since the frequency of this increased component is 1018 MHz, which is below the cutoff frequency of 1.17 GHz for the beam pipe, it cannot be absorbed by the SiC HOM damper. This build-up effect is estimated from the absorbed heat measured at the HOM dampers, but it has also been found that there are cavity-to-cavity variations.

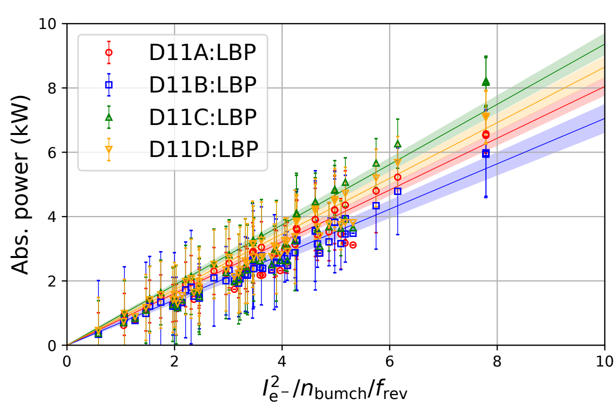

Figure 3: The prediction of HOM power of LBP ferrite damper at D11 side with linear fitting of data to 2024 winter run data in Fig 2.

In particular, the LBP side HOM damper of the seventh cavity from the upstream start, known as D11C (the second from the downstream side), is subject to a significantly larger effect as shown in Fig 3. However, the high-current operation conducted during the 2024 winter run exhibits a slight deviation from the linear fitting line observed in earlier data. If this deviation is genuine, the LBP side ferrite HOM damper alone would experience a load of approximately 30 kW at the design beam current. This is a significant unresolved issue that requires further investigation.

PLAN & SUMMARY

SuperKEKB is the high current and high luminosity accelerator machine. HOM damped superconducting cavities contribute to that stable and high current operation. In 2024 winter run, the beam current increased 1.3 A in electron ring as HER. In the SuperKEKB operation, the increased beam current has led to a significant rise in HOM power generated in the superconducting cavities. To mitigate this, SiC HOM dampers have been installed between cavities to absorb the propagating HOMs, and have proven effective in reducing the load on the ferrite dampers. In the future, SiC HOM dampers are planned to be installed downstream of every superconducting cavity. The effect of bunch spacing on HOM build up has been observed for LBP ferrite damper. And this effect cannot be absorbed by the SiC dampers. A detailed study of these issues has been started through simulation and data analyses. However, measurements during the 2024 winter high current run revealed an unexpected increase at D11C in the absorbed HOM power, deviating from previous linear predictions, which presents a concern. For next operations, data collection will be carried out using the analysis techniques and simulation established based on these experiences.

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