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OPERATING EXPERIENCE OF SRF SYSTEM AT HIGH BEAM CURRENT IN SuperKEKB

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Abstract

SuperKEKB aims for high luminosity on the order of 10^{35} /cm^2/s with beam currents of 2.6 A for electron and 3.6 A for positron to search new physics beyond the Standard Model in the B meson regime. In recent operations, we achieved a new record of luminosity of 4.65×10^{34} /cm^2/s with 1.1 A for electron and 1.3 A for positron. The SRF system that was designed for KEKB, the predecessor of SuperKEKB, is operating stably with the high beam currents owing to the measures against the large beam powers and the large higher-order-mode (HOM) powers. As a measure against the large beam powers, our SRF cavities have increased a coupling of high-power input couplers during the KEKB operation. As a measure against the large HOM power, newly developed SiC HOM dampers have been installed in the SuperKEKB ring. In addition, we have established the horizontal high-pressure rinse method to recover the cavity performance that has degraded due to vacuum works and accidents in the long-term operation. In this report, we will present our operation experience of SRF system under the high beam currents.

INTRODUCTION

The SuperKEKB accelerator that is an electron-positron asymmetric energy collider is an upgraded machine from KEKB accelerator aiming for a significant increase of luminosity. SuperKEKB main ring consists of a 7 GeV electron ring (high energy ring, HER) and a 4 GeV positron ring (low energy ring, LER). To achieve high luminosity, the designed beam currents are increased to 2.6 A for HER and 3.6 A for LER [1]. A full-scale collision experiment has been continued since 2019. In recent operation, the achieved beam currents are 1.14 A for HER and 1.46 A for LER, and the peak luminosity of 4.65×10^{34} /cm^2/s was recorded [2, 3].

The RF system of SuperKEKB is operating stably at large beam current of higher than 1 A in 2022 operation [4]. The RF-related operation parameters in KEKB (achieved) and SuperKEKB (design) are shown in Table 1. The design beam current is nearly twice as high as the KEKB achieved, and the beam power becomes large accordingly [5–7]. The RF system of HER consisting both of eight superconducting cavities (SCC) [8,9] and normal-conducting cavities (ARES) [10–12] has been reused from KEKB with reinforcement to handle the high beam current and the large beam power.

Because the beam power can be shared with SCC and ARES by giving phase-offset, the load of the input coupler of SCC will be almost the same as KEKB. On the other hand, the HOM power excited in the SCC module at the design current is estimated to be more than double the power achieved in KEKB, and to be unacceptable loads of the existing ferrite dampers. Then, additional SiC dampers are installed to reduce the load of ferrite dampers.

In this report, the operation status and experiences of SRF system under the high beam current are described.

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SCC MODULE

A cross sectional view of the SCC module is shown in Fig. 1 [13]. The SCC module was designed for KEKB with HOM damped structure equipped with a pair of ferrite HOM dampers on both small beam pipe (SBP) and large beam pipe (LBP) [14]. The eight SCC modules are operating in HER. In the latest beam operation in 2022, each SCC provided an RF voltage of 1.35 MV and delivered the beam power of ~260 kW in the maximum beam current of 1.14 A so far. Figure 2 shows the power delivered to the beam by each SCC module as a function of the stored beam current.

Input Coupler

The coaxial antenna-type input coupler was also developed for KEKB based on the input coupler of SCC in TRISTAN. The features of the input coupler are summarized in Ref. [15, 16]. Figure 3 shows the input coupler designed

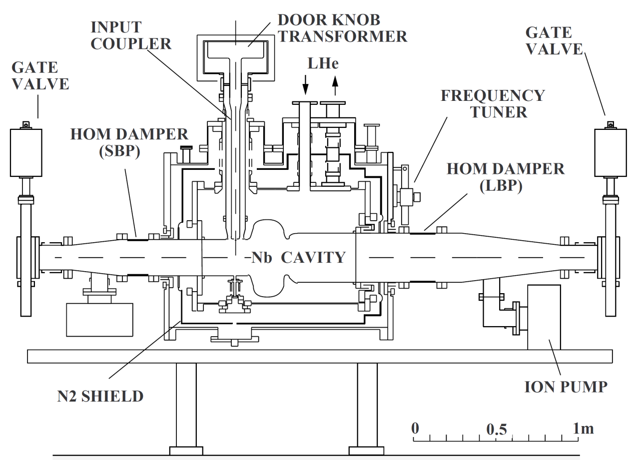

Figure 1: Cross-sectional view of HOM damped SCC designed for KEKB. This cavity is used for SuperKEKB. Ferrite HOM dampers are equipped on both SBP and LBP. The SBP and LBP diameters are 220 mm and 300 mm, respectively.

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Table 1: RF-related machine parameters achieved at KEKB [13] and those of the design values in SuperKEKB [7]. The eight SC cavities are operating in HER (electron ring).

		KEKB (achieved)				SuperKEKB (design)			
Parameters	**Unit**	**LER**	**HER**			**LER**		**HER**	
Beam energy	GeV	3.5		8.0		4.0		7.0	
Beam current	A	2.0		1.4		3.6		2.6	
Bunch length (σ_z)	mm	6–7		6–7		6		5	
Number of bunch		1585		1585		2500		2500	
Total RF voltage	MV	8		13–15		10–11		15	
Energy loss/turn	MV	1.6		3.5		1.76		2.43	
Total beam power	MW	3.3		5.0		~8		~8	
RF frequency	MHz	508.9				508.9			
Revolution frequency	kHz	99.4				99.4			
Cavity type		ARES	ARES		SCC	ARES		ARES	SCC
No. of cavities		20	10	2	8	8	14	8	8
Klystron : cavities		1:2	1:2	1:1	1:1	1:2	1:1	1:1	1:1
No. of klystron stations		10	5	2	8	4	14	8	8
RF voltage/cavity	MV	0.4	0.31	0.31	1.24	~0.5	~0.5	~0.5	1.3–1.5
Beam power/cavity	kW	200	200	550	400	200	600	600	400
R/Q of cavity	Ω	15	15	15	93	15	15	15	93
Loaded Q (Q_L)	$\times 10^4$	3	3	1.7	~5	3	1.7	1.7	~5

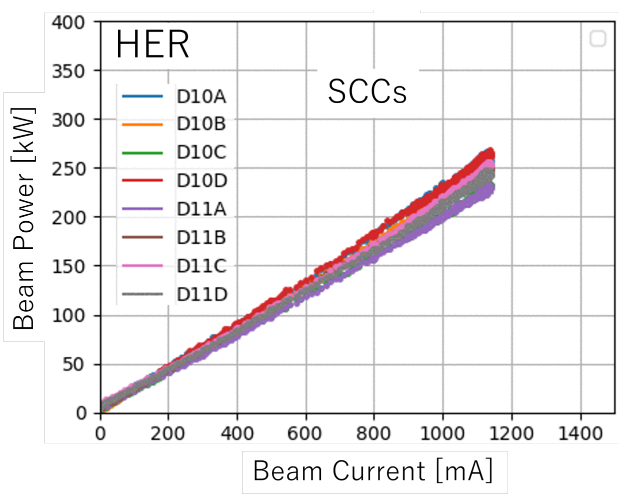

Figure 2: Beam power of each SCC module as a function of the stored beam current in HER. The beam power is obtained by subtracting the reflected power from the cavity from the klystron output power.

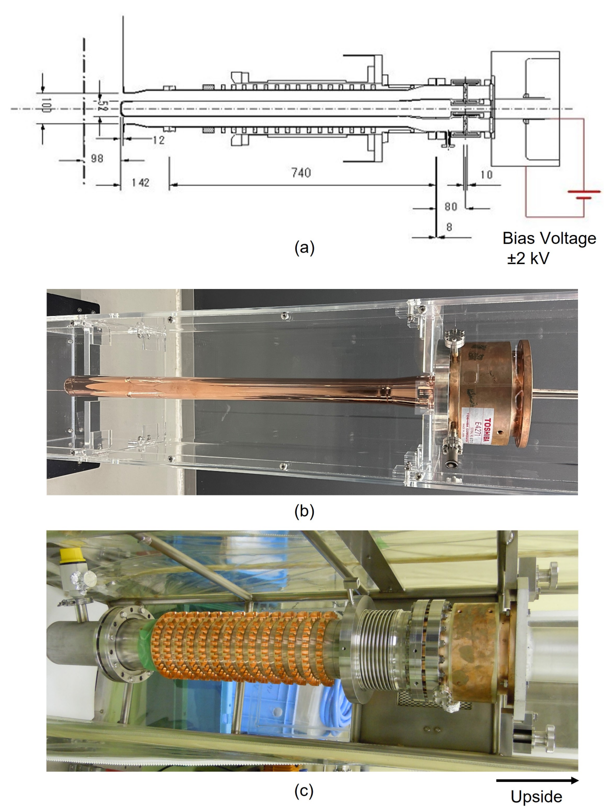

Figure 3: Coaxial antenna-type input coupler for KEKB and SuperKEKB. The cross-sectional view (a), the inner conductor (b) and after assembled with the outer conductor with cooling fin (c).

for KEKB. The input coupler which was assembled with the inner and the outer conductors was conditioned up to 800 kW in the traveling wave mode. Then, the input coupler was installed to the cavity module and conditioned up to 300 kW under the total reflection mode. The original external Q-value had been chosen as 7×10^4 to satisfy the desired voltage of 1.5 MV and the beam power of 240 kW at the design beam current of 1.1 A for KEKB. However, the beam current of KEKB was to be increased more than the design current to achieve higher luminosity. In 2004, the external Q was lowered to 5×10^4 to increase the delivering power to

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400 kW [13]. Coupling of the input coupler is variable by replacing the vacuum sealing gasket with a different thickness one to change the penetration of the inner conductor into the cavity. Finally, the maximum beam current was 1.4 A and the delivered beam power reached 400 kW/cavity [9]. In SuperKEKB, although the design beam current is twice higher than the maximum current of KEKB, the beam power delivered by SCC can be kept by sharing with ARES cavities by giving the phase-offset.

HOM Damper

The handling large HOM powers induced by the high beam current is one of the main issues. In KEKB, the HOM-damped structure which is the single cell cavity with large-diameter beam pipes was adopted for SCC design as shown in Fig. 1. The large diameter of the iris (220 mm) was optimized to propagate the mono-pole modes (TM_{011} and TM_{020}). On the one side of the beam pipes, a 300-mm-diameter beam pipe (LBP) is attached to extract the lower dipole modes (TE_{111} and TM_{110}). In this design, all HOM modes propagate out of the cavity and are damped by a pair of HOM dampers made of ferrite (Fig. 4). The details of the development of ferrite damper are summarized in Ref. [14]. In the KEKB operation, the absorbed power in 1.4 A-operation reached 16 kW without any problems [9].

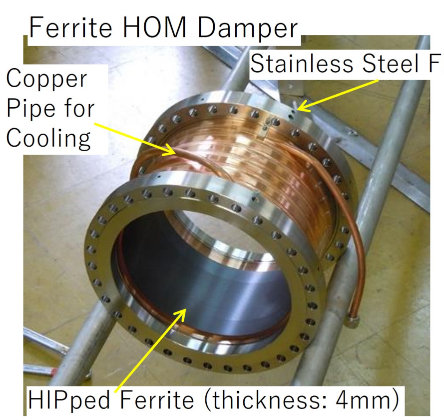

Figure 4: A KEKB type damper for SBP with 4-mm thickness of ferrite, inner diameter of 220 mm, length of 120 mm.

According to the power flow simulation in one cavity module, the load of the existing ferrite dampers is around 20 kW, which is not much increased from the maximum absorbed power in KEKB operation. But large HOM power is emitted through the downstream beam duct and the power becomes additional load of the dampers of downstream cavity [17]. To reduce the emission power, two sets of additional HOM dampers made of SiC have been installed to the downstream of two SCC modules (Fig. 5) [18, 19].

The HOM power absorbed by the ferrite dampers of downstream cavities were reduced by more than 10% by the additional SiC dampers as shown in Fig. 6. The absorbed HOM power by a pair of ferrite dampers in one SCC module was ~8 kW at the maximum beam current in 2022 [4]. To achieve

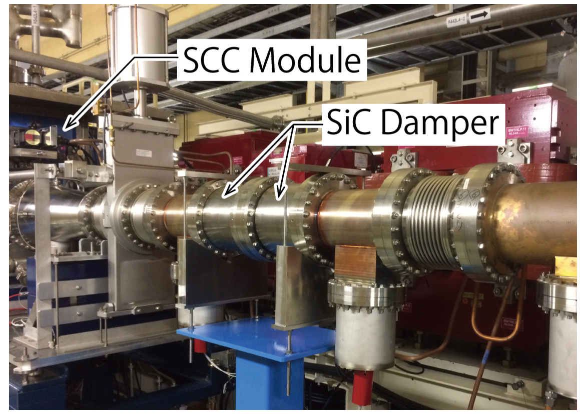

Figure 5: A set of SiC damper ducts installed to the downstream of a SCC module. Two SiC damper with a length of 120 mm are connected together. The inner diameter is 150 mm. The electron beam is coming from the left to the right direction. There are other SCC modules at the downstream of the beam.

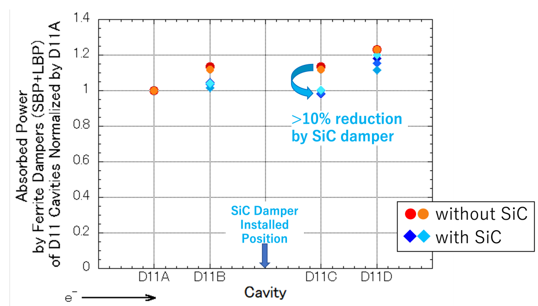

Figure 6: Ratio of absorbed HOM power by ferrite dampers of SCC cavities in D11 section. The load of ferrite dampers of D11C module which is the downstream of SiC damper was reduced.

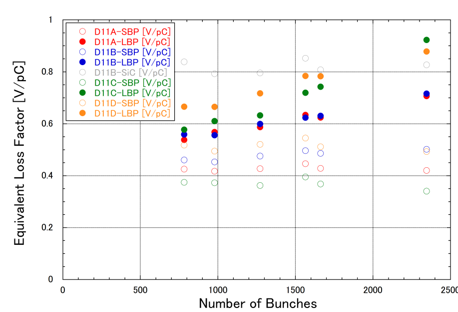

Figure 7: The equivalent loss factors (Eq.LF) of dampers as a function of the number of bunches. The Eq.LF of LBP dampers show the bunch number dependence.

the design beam current, SiC dampers will be installed to downstream of all cavities.

In the operation in 2022, the beam current was gradually increased while increasing the number of bunches to maintain the bunch current. A bunch number dependence was observed for the first time in the absorbed power of the LBP-ferrite dampers [20]. Figure 7 shows equivalent loss

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factors (Eq.LF) of each damper as a function of the number of bunches. Here, the Eq.LF is defined as a ratio of the absorbed power in each damper to the product of the bunch charge and the beam current. The larger the bunch number is, the higher the absorbed power becomes, i.e., the larger the Eq.LF. This dependence is attributed to bunch spacing, and it is assumed that the buildup of the HOM power occurs at short bunch spacing [21]. We are studying the bunch number dependence by simulations and accumulating data in beam operations to estimate the HOM power at a further current increase.

Cavity Performance Recovery

Another issue is the degradation of the cavity performance of Q_0. In the long-term operation since 1998, SCC modules experienced several vacuum works and troubles. As a result, the performance of several cavities degraded with strong field emission. To recover the cavity performance, we developed the horizontal high-pressure rinse (HHPR) method [22]. By HHPR, the performance of three cavities has been successfully recovered as shown in Fig. 8 and those cavities are operating stably in SuperKEKB.

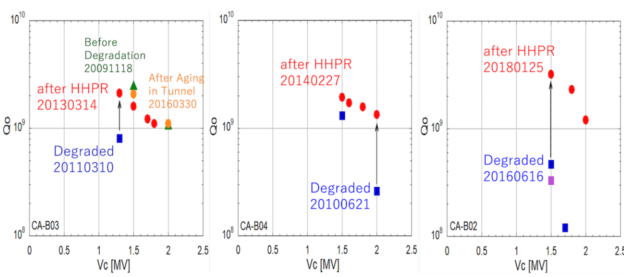

Figure 8: Q_0 values as a function of V_c before and after HHPR for three degraded cavities.

RECENT CAVITY OPERATION

The SCC is required to provide stable RF voltage and beam power. In order to maintain stable cavity operations, 1) warming up the system to room temperature is performed twice a year, 2) safety inspections due to high-pressure safety regulations of cryogenics are carried out once a year, 3) the input coupler conditioning before cooling with bias voltage is performed and 4) regular cavity conditioning every 2 weeks is carried out in the beam operation term.

RF Conditionings

Regular conditioning of the input coupler and the cavity is essential to maintain stable long-term operation. In Ref. [9, 13], the methods of conditioning are summarized. The input couplers are conditioned at room temperature up to 300 kW under total reflection conditions. A DC voltage within up to ±2 kV is applied between the inner and outer conductors of the coupler during the conditioning process. RF processing with bias voltage, called bias aging, is effective in expanding the multipacting area along the coaxial line to release the condensed gas on the coupler surface [15].

The cold cavity is conditioned with RF power not only just after cooling but also on the regular maintenance day every two weeks. In the maintenance aging, three cycles of increasing the cavity voltage to 2 MV are performed. And, the tuning phase is scanned within ±30° to move the standing wave in the coupler.

Beam Operation Statistics

In the recent beam operation, the RF system including SRF is operating stably without any troubles requiring long shutdown. In the operation in 2022, the beam current was gradually increased while increasing the number of bunches, finally achieved up to 1.14 A for HER with 2346 bunches. The cavity voltage of SCC was 1.35 MV/cavity. For the maximum beam current, the beam power was reached to ~260 kW in a SCC (Fig. 2). The trip rate due to breakdown was ~0.9/cavity for the eight SCCs in four months operation. The trip rates of cavities including ARES are not changed significantly since KEKB operation.

Trip Analysis

In the beam operation, the RF signals are monitored by oscilloscopes every beam aborts to analyze the cause of trip. Figure 9 shows an example of a trip by multipacting in a cavity. The spike of V_c (cavity pickup) signal was found ~40 ms before RF turned off by the interlock from the breakdown detector (Fig. 9(a)). It is supposed that the multipacting occurred and disappeared in a few tens of microseconds (Fig. 9(b)), and the local normal conducting region generated by the multipacting gradually propagated, increasing the cavity wall loss. Finally, an increase in klystron output power was observed as a result of feedback control to keep V_c constant (Fig. 9(c)). It is important to detect malfunctions of SRF system quickly by the diagnostic system in order to continue stable operation at high beam currents.

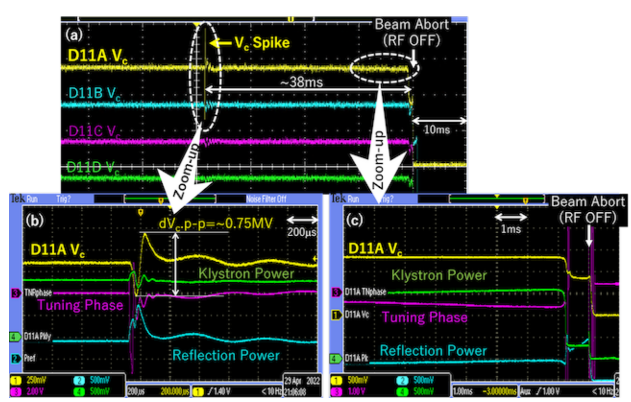

Figure 9: Example of RF signals of a trip event of D11A cavity monitored by oscilloscopes; (a) long-range monitor of V_c of 4 cavities, (b) focused on V_c spike event, (c) focused on just before beam abort. The V_c (yellow), klystron output power (green), cavity reflection power (cyan) and cavity tuning phase (magenta) are indicated in (b) and (c).

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SUMMARY

SuperKEKB is increasing the beam current and continues to update the luminosity record. In 2022 operation, the RF system of SuperKEKB is operating stably at large beam current of 1.14 A for HER and 1.46 A for LER. The SCC system is operating stably in HER with low trip rates with regular maintenance aging. The major issues against the large beam current are the large HOM power and the degradation of the cavity performance. It is confirmed that the additional SiC HOM dampers for SCC reduce HOM load of ferrite dampers of downstream cavities. In the future, SiC dampers will be installed to downstream of all cavities to increase the beam current. The HHPR is established to recover the cavity performance of Q_0. Three HHPRed cavities are operating stable for the beam operation. For the stable beam operation and the future beam current increase, the estimation and evaluation of the HOM power is an important issue.

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