ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEXAS0102

SuperKEKB OPERATING EXPERIENCE OF RF SYSTEM AT HIGH CURRENT

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Abstract

SuperKEKB aims for high luminosity on the order of 10^{35} /cm^2/s with high beam currents of 2.6 A for electron and 3.6 A for positron to search a new physics beyond the Standard Model in the B meson regime. In recent operations, we achieved new record of the luminosity of 4.7×10^{34} /cm^2/s with 1.1 A for electron and 1.3 A for positron. The RF system that is basically reused from KEKB is operating stably in the high current operation owing to the measures against to large beam power and HOM power. To cope with the large beam power, it has been increased the number of klystrons that drive only one normal conducting cavity (ARES) and reinforced the input couplers of ARES. As a measure against HOM power, the additional HOM dampers have been installed to superconducting cavities. One-third of LLRF control systems have been replaced with newly developed digital system to improve accuracy and flexibility. New damper system for coupled bunch instability expected in high current has been installed to new digital system. In this report, operation status of RF system under the high current operation will be presented.

INTRODUCTION

The SuperKEKB accelerator that is an electron-positron asymmetric energy collider is an upgrade 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 beam currents are designed as 2.6 A for HER and 3.6 A for LER [1]. The first commissioning beam operation without collision was performed in 2016 as Phase-1. After the Belle II detector rolled in, Phase-2 beam operation started and the first beam collision event was observed at Belle II in 2018. A full-scale collision experiment (Phase-3) 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-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 [4–6]. The RF system consisting both of normal-conducting cavities (ARES) [7–9] and superconducting cavities (SCC) [10, 11] has been reused from KEKB with reinforcement to handle the high beam current and the large beam power. The ARES stations have 1:2 configuration in which one klystron drives two ARESs, and 1:1 configuration in which one klystron drives one ARES. The SCC station has one cavity driven by one klystron.

The main upgrade items are as follows:

- Increasing the number of RF klystron stations of ARES 1:1 configuration.
- In ARES, changing input coupling factor β from 3 (1:2 configuration) to 5 (1:1 configuration).
- In SCC, installation of additional higher-order-mode (HOM) dampers.
- In High-Power RF (HPRF) system, replacement of deteriorated klystrons with higher gain and more stable ones.
- In Low-Level RF (LLRF) system, replacing with new digital LLRF system in a part of ARES 1:1 stations and development of new damper system for coupled instability.

The addition of klystron to upgrade from ARES 1:2 to 1:1 configuration and the increase of input coupling factor of ARES are essential to provide the large beam power. 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 exceed the allowable power of the existing ferrite dampers. Then, additional dampers are necessary to reduce the load of ferrite dampers. The replacement of the old HPRF and LLRF systems with new systems increases the stability and accuracy of beam operation.

The layout of RF stations in SuperKEKB at present is shown in Fig. 1. There are a total of 30 RF klystron stations consisting 16 ARES (22 cavities) stations in LER and 6 ARES (8 cavities) and 8 SCC stations in HER. To date, the number of ARES 1:1 station is partially increased to 10 (LER) and 4 (HER) stations. In addition, countermeasures against RF-related instabilities in LLRF are essential for the high beam current operation. These measures have been completed partially. Remaining update items will be performed in the future to achieve the target beam current and luminosity. The details of upgrade of each component are described in Refs. [9, 13–18]. In this report, the operation status of RF system and the high beam current-related issues in RF system are described.

OPERATION STATUS OF RF SYSTEM

In the recent beam operation, the RF system is operating stably without any troubles requiring long shutdown.

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Table 1: RF-related machine parameters achieved at KEKB [12] and those of the design values in SuperKEKB [6].

		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	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 poser/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

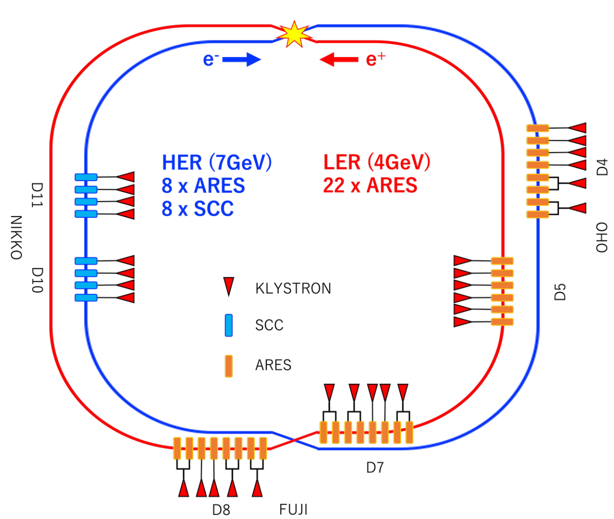

Figure 1: Layout of RF system of SuperKEKB. There are a total of 30 RF stations consisting both of normal-conducting cavity (ARES) and superconducting cavity (SCC) stations.

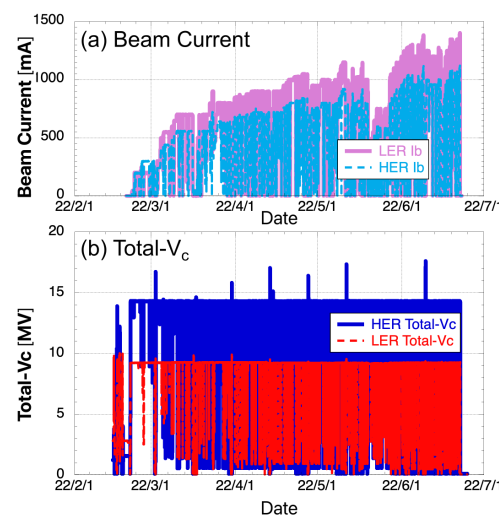

Figure 2: Operation history of 2022ab run. (a) shows beam current of LER (pink) and HER (cyan). (b) indicates total-V_c of LER (red) and HER (blue). The spikes in total-V_c are correspond to cavity aging in regular maintenance day.

Figure 2 shows the history of the beam current and total-V_c for both rings in the run of 2022ab (from Feb. to June 2022). In this run, the beam current was gradually increased while increasing the number of bunches, finally achieved up to 1.46 A for LER and 1.14 A for HER with 2346 bunches. The total-V_c for both rings were kept as 9.12 MV for LER and 14.2 MV for HER through this run. After middle of April, although one of ARES 1:1 stations (D07C) in LER was detuned (parked) due to a problem with the control system of the klystron power supply, the total-V_c was able to be maintained by increasing the voltage of other cavities. The voltage of each ARES cavity was 0.40–0.45 MV/cavity. In SCC, the cavity voltage was 1.35 MV/cavity. The spikes of total-V_c shown in Fig. 2(b) are correspond to cavity aging in regular maintenance days. The drop downs of total-V_c are the results of beam aborts. When the beam higher than 300 mA is aborted (dumped instantaneously), the RF is turned off by the interlock of the reflection power from the cavity in almost all RF stations. Conversely, if the interlock works even at one RF station and the RF is turned off, the beam of the corresponding ring is aborted.

Figure 3 shows the power delivered to beam by each cavity as a function of the stored beam current. For the maximum

65th ICFA Adv. Beam Dyn. Workshop High Luminosity Circular e+e− Colliders eeFACT2022, Frascati, Italy JACoW Publishing
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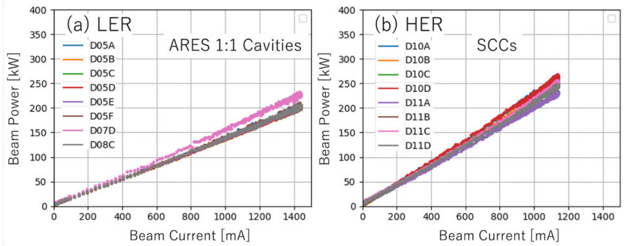

Figure 3: Beam power of each cavity as a function of the stored beam current. (a) shows ARES 1:1 cavities in LER. (b) shows SCCs in HER. The beam power is obtained by subtracting the reflected power from the cavity and the cavity wall loss from the klystron output or cavity input power.

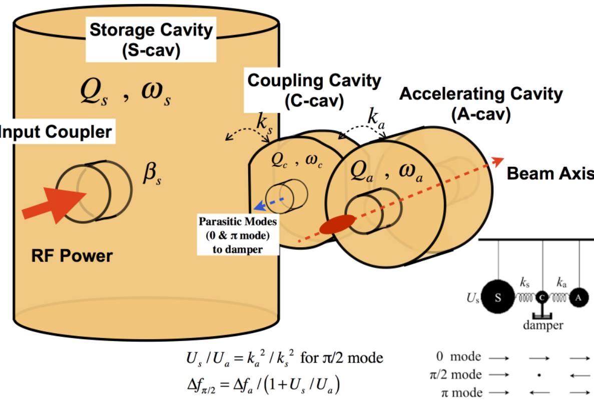

Figure 4: Illustration of the ARES cavity structure.

beam current, the beam power was reached to ~230 kW in an 1:1 ARES cavity in LER (Fig. 3(a)) and ~260 kW in a SCC in HER (Fig. 3(b)). In higher beam current operation, the optimization of the beam loading balance among the RF stations will be essential for stable and efficient beam operation. The optimization tool has been established and used in the actual beam operation [19].

All beam aborts are analyzed by recording the RF and beam signals to find the cause of trip. In particular, in ARES stations with digital LLRF system, all RF signals are recorded with a resolution of around 0.1 µs in maximum before and after events such as abort and RF off [16]. The fast-signal monitor is very useful as a diagnosis tool for the RF system. The number of beam aborts caused by the RF system was ~10% of all aborts (725 aborts in 2022ab), excluding manual and low current (<50 mA) aborts. The ~35% of the RF aborts were due to breakdown of ARES cavities and SCCs. In the 2022ab operation, the trip rates due to breakdown were ~0.5/cavity for the 30 ARES cavities and ~0.9/cavity for the 8 SCCs in four months operation. The trip rates of cavities are not changed significantly since KEKB operation. The ~40% of the RF aborts were due to HPRF system including incorrect operation of the interlock system of the klystron power supply system. As mentioned above, in 2022ab run, one klystron station was disconnected from the beam operation because the heater power supply of the klystron was broken due to a control board failure. One of the causes of problems on the HPRF system is the deterioration of the devices and infrastructure due to aging. Also in LLRF system, the aging of analog control modules is main cause of the failures. For stable operation, regular inspections and updating of devices are being carried out throughout the RF system.

ARES CAVITY

The ARES is a unique cavity, which is specialized for KEKB [7, 8]. It consists of a three-cavity system operated in the $\pi/2$ mode: the accelerating (A-) cavity is coupled to a storage (S-) cavity via a coupling (C-) cavity as shown in Figure 4 [9]. The A-cavity is structured to damp HOM. The S-cavity with a large stored energy plays a role in suppressing the optimum detuning of accelerating $\pi/2$ mode ($f_{\pi/2}$). Corresponding to the stored energy ratio of $U_s/U_a = 9$, where U_s and U_a are stored energies of S- and A-cavities, the detuning of $\pi/2$ mode ($\Delta f_{\pi/2}$) is one tenth that of A-cavity (Δf_a). As a result, the coupled bunch instabilities driven by the accelerating mode is suppressed. The C-cavity is equipped with a damper to damp parasitic 0 and π-modes. The $\pi/2$ mode has a high Q value of ~110,000 and a low R/Q value of 15 Ω.

The high-power input coupler has been upgraded to cope with the large beam power of SuperKEKB. At the design beam current, the beam power of 1:1 ARES is estimated as 600 kW in a cavity and the input power become to be 800 kW including the cavity wall loss of around 150 kW. In order to increase the input power from 400 to 800 kW, the coupling factor β of the input coupler has been increased from 3 to 5 [6, 14]. In addition, to suppress multipactoring problem in the coaxial lines of the couplers, the fine groove structure is adopted for the outer conductor surface (Fig. 5) [13]. 14 of the 32 input couplers have been upgraded with an increased coupling factor β of 5 and the fine groove structure. Those new input couplers have no multipactoring and other problems in SuperKEKB beam operation so far.

At higher beam current operation, diagnostic tools will become more important. In the ARES system, all input couplers are monitored with TV or network cameras attached to the viewport of S-cavity on the opposite side of the input coupler. A few seconds of video of the camera before and after the RF is turned off is automatically recorded on mass storage devices. Figure 6 shows examples of the recorded videos with the cameras. This diagnostic tool can isolate the problem; it is related to the input coupler or not. Another diagnostic tool is fast-signal recording by the digital LLRF. Figure 7 shows examples of the fast signals with a microsecond resolution. When the RF switch is turned off due to a reason other than the cavity, the field falls with a tail determined from the fill time (~10 µs) as seen in Fig. 7(a). On the other hand, as seen in Fig. 7(b), the field drops in a much shorter time than the fill time, which can be understood as an occurrence of cavity breakdown due to vacuum arc.

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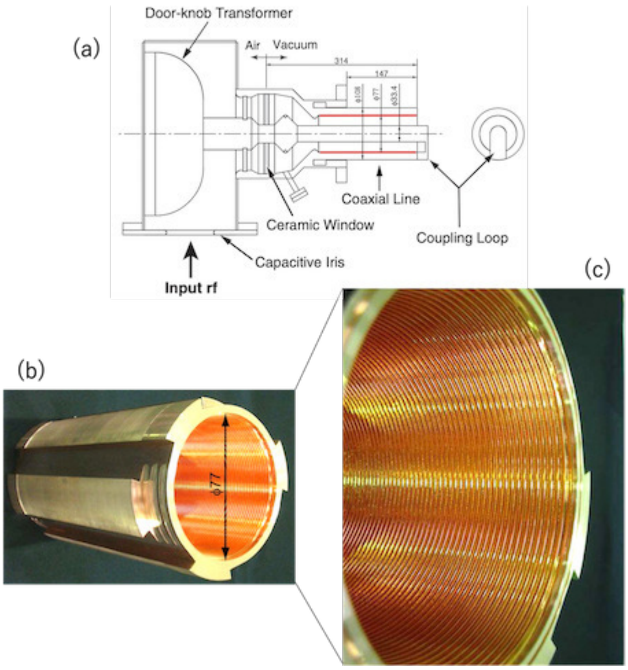

Figure 5: Schematic view of input coupler for the ARES(a), outer conductor with fine grooving (b) and zoom of fine grooving(c). The red line in (a) indicate the fine grooving structure.

(a) (b)

Figure 6: Examples of the recorded videos with the cameras attached to the viewport of S-cavity on the side opposite the input coupler at the moment of cavity trips. (a) Clear discharge from multipactoring on the RF window in the input coupler was observed. (b) Lights came not from the input coupler but some other place with scattered reflection.