KEKB SUPERCONDUCTING ACCELERATING CAVITIES AND BEAM STUDIES FOR SUPER-KEKB

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Abstract

Eight superconducting accelerating cavities have been stably operated in the KEKB with sufficiently low trip rates. Two superconducting crab cavities were installed in 2007 and soon the crab crossing operation started. Recently the KEKB luminosity reached the world record of $2.1 \times 10^{34}/cm^2/s$. Stable operations of the accelerating cavities contributed for the luminosity increase. For the future Super-KEKB, we are developing a high power coupler for the input power more than 400 kW and a HOM damper for RF power absorption more than 30 kW. The Super-KEKB requires RF operations with the high beam loading and the low RF voltage than the present KEKB operation. To suppress klystron output powers the external Q value has to be reduced. A new operation was proposed for superconducting cavities. In order to keep high RF voltages in each cavity, some cavities reverse its synchronous beam phase while the total RF voltage is kept as low as the required one. Beam studies were successfully carried out with one cavity reversed its synchronous beam phase.

INTRODUCTION

KEKB, an energy-asymmetric electron-positron double ring collider for B-factory, was commissioned in December 1998. Four heavily-damped superconductiong accelerating cavities (SCC) were installed in the high energy electron ring (HER). Another four cavities were installed in 2000 [1]. A hybrid RF system of eight superconducting cavities together with twelve normal conducting cavities (ARES) provided the total RF voltage of 13-15 MV. The maximum current stored in the HER is 1.4 A [2]. Two crab cavities ware installed and KEKB started crab crossing operation in 2007 [3]. The HER beam currents gradually increased to 1.25 A with crab cavities. KEKB recently achieved the world luminosity record of $2.1 \times 10^{34}/cm^2/s$ with crab crossing and exceeded the total integrated luminosity of 1 ab^{-1}. SCC cavities were operated stably during the crab crossing operation.

KEKB machine will be up-graded to a higher intensity machine, Super-KEKB. Its design luminosity is $8 \times 10^{35}/cm^2/s$. To meet requirements of the upgraded machine, several R&D are underway. One is for a high power HOM damper for higher beam currents. Another is for a high power input coupler for higher beam powers. Finally, we proposed a new operation mode of the SCC cavities for Super-KEKB. Synchronous beam phase of several SCC cavities are reversed to maintain high accelerating RF voltage. This paper presents present status of the SC cavities at KEKB and R&D for Super-KEKB.

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SUPERCONDUCTING CAVITY

SCC cavity is a superconducting, heavily HOM damped cavity for KEKB. The cavity has a single cell, large beam pipes and ferrite RF dampers (HOM damper) for HOM damping and a coaxial-type input coupler for feeding high beam powers. Figure 1 shows a cross sectional view of the SCC. Eight SCC and twelve ARES cavities are installed in the HER to provide the total RF voltage of 13-15 MV and the total beam power of 5 MW. SCC cavities were operated stably for more than ten years. The maximum beam current is 1.4 A and maximum beam power is 400 kW. The maximum HOM power absorbed in HOM dampers is 16 kW. Table 1 summarizes achieved RF parameters.

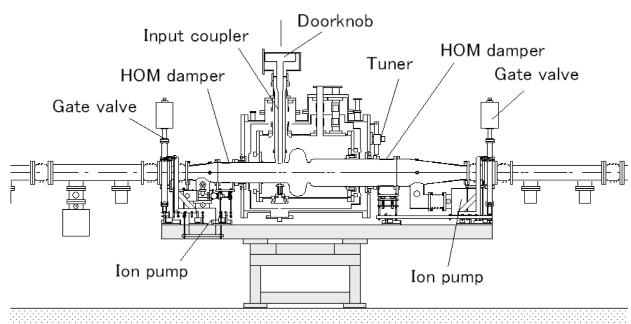

Figure 1: A cross sectional view of the KEKB superconducting accelerating cavity. A 509 MHz single cell cavity with a large iris diameter of 220 mm has ferrite HOM absorbers on both sides and a coaxial-type input coupler.

Table 1: Achieved Parameters of the KEKB SC Cavities

Parameter	design r	achieved	unit
Beam current	1.1	1.4	A
Bunch length	2	10	nC
RF voltage	1.5	1.2-2	MV/cav.
Beam loading	250	400	kW/cav.
HOM power	5	16	kW/cav.

The cavity was stably operated at high current of 1.4 A. The trip rate was 0.5 times/day. KEKB started crab crossing operation since 2007 with the HER beam currents of around 1A. The trip rate during this operation was 0.1 times/day. About half of the trips were caused by the high voltage discharge in the cavity or in the input coupler, while the other half was caused by the failure of the RF source or the refrigerator system.

R&D FOR SUPER-KEKB

The present KEKB machine will be upgraded to Super-KEKB machine, which has lower emittance to increase luminosity (nano-beam option). The RF parameters for the HER ring are listed in table 2. The big parameter changes are lower RF voltage (6.7 MV) and larger beam power (7.65 MW). Those requirements arise several difficulties for SCC operations. The coupling of the input coupler has to be replaced to the optimum coupling to minimize the klystron output power. The external Q factor of the input coupler has to be reduced to one third of the present value. Present inner conductors have to be replaced to longer ones for the larger coupling. There are risks of the performance degradation of the cavity from contamination, or possible heat up at the tip of the longer inner conductor. Another difficulty is about the detuning frequency. With those parameters, the detuning frequency becomes close to, or even larger than the revolution frequency. It excites the coupled bunch instability of the minus-one mode. A new operation mode, reverse phase operation (RPO), was proposed to avoid those difficulties. The synchronous beam phase ϕ_s of several cavities are reversed to $-\phi_s$. Figure 2 shows a phasor representation of each cavity voltage and the total voltage. The total RF voltage is a sum of each cavity voltage. With reverse phase cavities, each cavity can have high voltage and share equal beam power, while the total voltage is still kept as low as the required one. The merit of this operation is that we can choose the cavity voltage so that the optimum coupling can be set near the present value. The detuning frequency also can be suppressed. Three cavities will be operated with reverse phase at Super-KEKB.

Table 2: RF Parameters of Super-KEKB

Parameters		Unit
Beam energy	7.0	GeV
Beam current	2.62	A
# of bunches	2503	
Total beam power	7.65	MW
Total RF voltage	6.7	MV

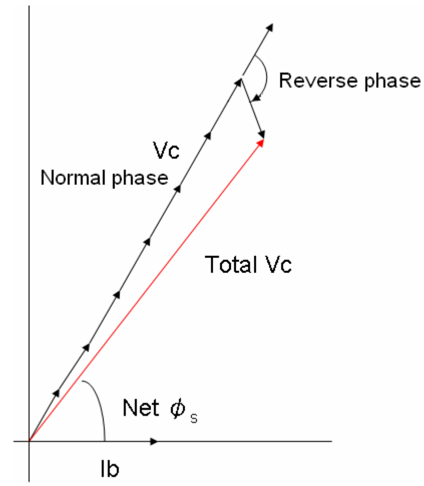

Figure 2: Phasor representation of the cavity voltage. The synchronous beam phase of one cavity is reversed. Each cavity has the large RF voltage, while the total voltage is kept as low as the required value.

Beam Studies for RPO

Several feasibility studies for RPO have been conducted. Cavity voltages and phases were set for eight SCC cavities with one cavity reversed its phase. Those parameters were set not to vary the total RF voltage in the HER with twelve ARES cavities. The low beam current up to 150 mA was stored and the klystron output powers of each cavity were monitored. The beam loading of the reverse phase cavity varied according to its beam phase. The beam phase was set to have equal beam loading of the normal state cavity. To check the stability, the beam phase was set at the zero beam loadings or over loaded state, however, in any state, the beam was accelerated stably. The RF voltage related parameters, such as synchrotron tune and bunch length were measured several times during the RPO studies. Those parameters did not vary within the measurement errors, that is, the total RF voltage was unchanged.

The RPO was tested at high beam currents to check the heavy beam loading phenomena and the transient behaviors at the cavity trip. The beam currents were stored at 500mA, 800mA and 1A and the beam was stably accelerated. Figure 3 shows transient behaviors of the input RF power, reflected RF power, tuner phase and cavity voltage of the reversed cavity when a normal state cavity was intentionally tripped. At the RF off of the normal state cavity, they begin to vary according to the beam phase change. The reflected RF power of the reversed cavity begins to increase, while that of the normal state cavity begins to decrease. The tuner phase begins to shift to positive direction. Those phenomena can be understood that the beam loading of the normal state cavity increases, while that of the reverse phase cavity decreases. The beam was aborted in 200 ms by the beam phase interlock. The significant difference between normal state cavity and reversed cavity is the variation of the cavity voltage. The RF voltage of the reverse phase cavity increases as shown in figure, while that of the normal phase cavity decreases. The voltage increase of the reverse phase cavity becomes larger as the beam current increases. Therefore the voltage increase might be a problem at Super-KEKB. However, its increasing rate seems to saturate. The voltage increasing rate depends on the operating RF voltage, the beam phase change, the beam current and the beam abort timing from the RF trip of the cavity. The maximum voltage increase of the reverse phase cavity was estimated to be at most 0.3 MV for the RF parameters of Super-KEKB. The voltage increase of the reverse phase cavity at the RF trip will be acceptable at Super-KEKB.

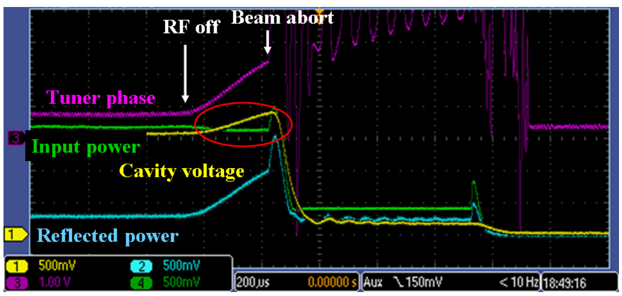

Figure 3: Transient behaviour of the input and reflected RF powers, the tuner phase and the cavity voltage of the reverse phase cavity. Voltage increase about 0.3 MV (shown by a red circle) was observed at the beam current of 1 A.

The RPO was applied at the high luminosity operation of KEKB for 6 days from Dec. 18 to 24, 2009. The RPO was stably operated and there were no beam aborts caused by the reverse phase cavity or normal state cavities. The maximum beam current of 1.2 A was stored in the KEKB HER. Each cavity delivered an RF power of 300 kW to the stored beam.

With those beam studies, we conclude that RPO is applicable at Super-KEKB.

HOM Damper

The designed bunch length (5mm in the HER) generates the HOM power of 46 kW in one cavity at 2.6 A with 2500 bunches. Those HOM powers have to be absorbed in the ferrite HOM dampers [4] attached in two beam pipes. The most serious issue is the out-gassing from the ferrite material. The out-gassing condenses on the cavity wall and triggers the high voltage breakdown. It is necessary to decrease surface temperature of the ferrite material for suppressing the out-gassing. We are developing a new HOM damper with ferrite thickness reduced from 4 to 3 mm and with a double cooling channel structure for efficient cooling of the ferrite surface. A prototype of the new damper with a ferrite thickness of 3 mm was fabricated and high power tested. The surface temperature was reduced by 25 % as shown in Figure 4. A prototype with the double cooling channel structure is being fabricated. This structure is expected to further reduce the surface temperature by 17 %. With those modifications, HOM dampers can absorb HOM powers without serious out-gassing at Super-KEKB.

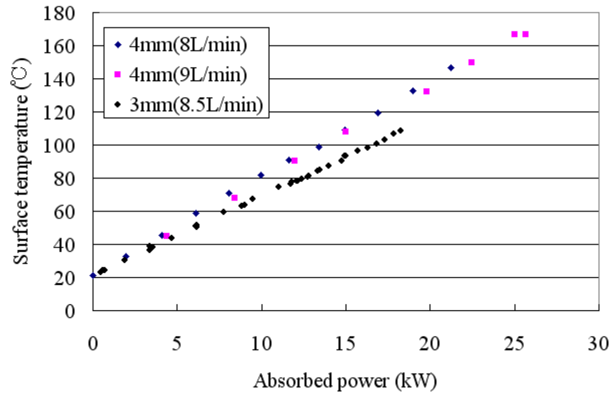

Figure 4: Surface temperatures of the ferrite material at several absolved RF powers. Ferrite thickness of 3 mm suppressed surface temperatures by 25 %. The flow rate of the cooling water is 8.5 L/min.

Input Coupler

Required beam power at Super-KEKB is 400 kW per cavity. The present input couplers [5] satisfy this power requirement. However it is desirable to handle more RF powers for a flexible operation of SCC. We continue to develop high power couplers. Recently, a new coupler, which has a single cooling path of the cooling water, was fabricated and RF conditioned up to 750 kW.

SUMMARY

Superconducting accelerating cavities for KEKB have been operated stably with sufficiently low RF trip rates. Those cavities with a new operation mode, reverse phase operation (RPO), and new HOM dampers will be used for the upgraded machine, Super-KEKB.

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