THE GROWTH POTENTIAL OF THE ARES CAVITY SYSTEM TOWARD SUPER KEKB

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Abstract

Normal conducting RF accelerating cavities named ARES (Accelerator Resonantly coupled with Energy Storage) have been operated to store high-current beams stably in the KEKB double-ring electron-positron collider with the design luminosity of $1\times10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The ARES cavity is based on a three-cavity system stabilized with the π/2-mode operation scheme, where a HOM-damped accelerating cavity is coupled with a large cylindrical energy storage cavity via a coupling cavity between. Together with the current operational performance of the ARES cavity, we discuss its growth potential toward the Super KEKB project of boosting the luminosity frontiers beyond $10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

INTRODUCTION

The operation of conventional normal conducting accelerating cavities with heavy beam loading would give rise to a serious problem with longitudinal CBI (Coupled Bunch Instability) due to the fundamental mode, other than the HOM-driven CBI. In electron storage rings, the resonant frequency of the accelerating mode is usually detuned downward with respect to the RF frequency f_{RF} to compensate for the reactive component of the beam loading. The optimum detuning Δf_a is given by

$$\Delta f_a = -\frac{I\sin\phi_s}{2V_c}\times\frac{R}{Q_0}\times f_{RF} = -\frac{P_b\tan\phi_s}{4\pi U}\ , \qquad (1)$$

where I is the beam current, ϕ_s the synchronous phase, V_c the cavity voltage, R the shunt impedance, Q_0 the unloaded Q value, P_b the beam power, U the stored energy. Loaded with the design beam current of 2.6 A for the KEKB LER (Low Energy Ring), the amount of detuning Δf_a required for the accelerating cavity would become about 2~3 times the beam revolution frequency f_{rev} = 99.4 kHz, leading to the strong excitation of longitudinal CBI with a growth time on the order of 100 μs, much faster than the radiation damping time of 23 ms.

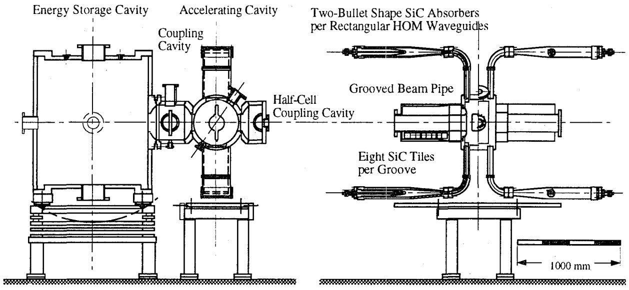

Figure 1: Front and side views of the ARES cavity system.

The ARES cavity developed as a countermeasure against this problem is based on a three-cavity system [1], where an accelerating cavity is coupled with a high-Q energy storage cavity via a coupling cavity between. Figure 1 shows the front and side views of the ARES cavity for KEKB. Its design is based on a high-power conceptual demonstrator ARES96 [2] with a cylindrical energy storage cavity operated in the TE_{013} mode. The accelerating mode is the π/2 resonant mode of the three-cavity system. According to an equivalent circuit model [1], the stored energy ratio for the π/2 mode is given by

$$U_s/U_a = k_a^2/k_s^2\ , \qquad (2)$$

where U_a is the stored energy in the accelerating cavity, U_s in the storage cavity, k_a the coupling factor between the accelerating and coupling cavities, and k_s between the storage and coupling cavities. The energy ratio for the π/2 mode can be kept almost constant against detuning by Δf_a for the accelerating cavity loaded with the beam. Therefore, the detuning for the π/2 mode will be reduced as

$$\Delta f_{\pi/2} = \frac{\Delta f_a}{1+U_s/U_a}\ . \qquad (3)$$

Actually, the design ratio $U_s/U_a = 9$ for the KEKB ARES cavity gives $\Delta f_{\pi/2}$ = -20 kHz, small enough compared with the revolution frequency, so that the growth rate of the severest −1 mode of the CBI can be reduced to a level of τ = ~10 ms where some RF feedback system [3] could damp it.

In KEKB, 20 ARES cavities have been successfully operated to store the positron beam up to 1.8 A in the LER, while 10 ARES cavities in combination with 8 superconducting cavities to store the electron beam up to 1.1 A in the HER (High Energy Ring). According to the operational performance so far, we will probably be able to manage with the current version of the ARES cavity for the Super KEKB HER with 4.1 A, 1.6 times the design beam current of 2.6 A for the KEKB LER. On the other hand, we need to upgrade the ARES cavity toward the Super KEKB LER with 9.4 A.

FUNDAMENTAL MODE ISSUES

The beam current of 9.4 A will be supported by 28 ARES cavities for Super KEKB, whereas 2.6 A to be supported by 20 ARES cavities for KEKB. With the heavier beam loading, the accelerating cavity itself needs to be further detuned by Δf_a = -200 kHz to -710 kHz. Consequently, the amount of detuning for the π/2 mode will become large comparable with the revolution frequency if the current energy ratio $U_s/U_a = 9$ unchanged. Therefore, the first upgrade item should be to increase the energy ratio further. The ARES cavity system can be mechanically separated into two cavity parts: the storage cavity and the accelerating cavity part with the coupling cavity brazed. We are planning to remodel the accelerating cavity part together with the HOM loads, whereas the storage cavity will be reused. Table 1 presents RF parameters for three cases with U_s/U_a = 9, 15 and 18. As the energy ratio being increased, the unloaded Q value Q_0 increases whereas the input coupling factor β decreases. According to a computer-aided simulation study, we need to increase the height of the rectangular aperture (width = 120 mm) between the accelerating coupling cavities from 160 mm to 175 mm for $U_s/U_a = 15$, to 182 mm for $U_s/U_a = 18$. Increasing the aperture height up to 185 mm is probably acceptable without significant changes to the fabrication. Figure 2 shows the real part of the coupling impedance of the $\pi/2$ mode, calculated for each case. As the energy ratio being increased, the detuning $\Delta f_{\pi/2}$ reduces less than one half of the revolution frequency, and furthermore the resonance becomes a little sharp. That is because the loaded Q value, $Q_L = Q_0/(1+\beta)$, increases as U_s/U_a being increased. Figure 3 shows the growth rates calculated for the -1, -2, and -3 modes of the CBI driven by the $\pi/2$ mode, plotted as a function of the energy ratio U_s/U_a. By increasing the energy ratio from 9 to 15, the growth rate of the -1 mode can be reduced by one order of magnitude to a manageable level with $\tau = 1.5$ ms. Balancing the relaxation in the growth rate and the increase in the cavity power P_c (see Table 1), the energy ratio U_s/U_a around 15 is favorable.

Another issue is about the parasitic 0 and π modes brought by the coupled-cavity scheme. Both parasitic modes can be damped with an antenna-type coupler attached to the center of the coupling cavity, whereas the $\pi/2$ mode does not couple to the coupler because of its field distribution with the electric-short boundary condition at the vertical mid plane of the coupling cavity. Furthermore, the 0 and π modes are located almost symmetrically with respect to the $\pi/2$ mode tuned into the vicinity of the RF frequency. Therefore, the impedance contributions from the damped 0 and π modes can be counterbalanced between the exciting and damping terms for the CBI. However, the field distributions of the 0 and π modes are subject to the first order term of tuning errors. For example, when the accelerating cavity is detuned by Δf_a, the first order term of perturbation is proportional to $\Delta f_a/(f_\pi - f_0)$. Therefore, the delicate counterbalancing may be deteriorated with heavier beam loading. Figure 4 shows the coupling impedance of the 0 and π modes calculated for three cases: $U_s/U_a = 9$ with 2.6 A, $U_s/U_a = 9$ with 9.4 A, $U_s/U_a = 15$ with 9.4 A. The impedance imbalance with respect to the RF frequency is also shown, where the positive to excite and the negative to damp, and the fastest growth time is indicated. The calculation was carried out as follows: the perturbation due to Δf_a was taken into account up to the first order; and the external Q value of the coupling cavity to the antenna coupler was assumed to be 50 (the same as for KEKB), which gives $Q_L = 100$ for the unperturbed 0 and π modes with $U_a = U_c$. As the accelerating cavity being detuned downward, the field distribution changes as $U_a > U_c$ for the 0 mode, whereas $U_a < U_c$ for the π mode, where the energy imbalance is proportional to $\Delta f_a/(f_\pi - f_0)$. For KEKB, the impedance imbalance is at an allowable level below 500 Ω/cavity, so that the CBI is expected to be suppressed well and actually has not been observed so far. For Super KEKB, the growth time will become 3.3 ms when $U_s/U_a = 9$. As U_s/U_a being increased to 15, it will be eased a little to 4 ms because $\Delta f_a/(f_\pi - f_0)$ roughly reduces as $\propto k_a^{-1}$, i.e. $\propto (U_s/U_a)^{-1/2}$. Anyway, some bunch-by-bunch longitudinal feedback will be needed to suppress the CBI due to the 0 and π modes.

Table 1: RF parameters of ARES cavity for Super KEKB LER.

U_s/U_a	9	15	18	
I		9.4 (2.6)		A
# of Cavities		28 (20)		
f_{RF}		508.887		MHz
h		5120		
V_c		0.5		MV
Q_0	1.11	1.27	1.32	$\times 10^5$
$(R/Q)_{\pi/2}$	15	9.4	7.9	Ω
input β	5.4 (2.7)	4.1	3.8	
P_c	150	210	240	kW
$\Delta f_{\pi/2}$	-72 (-20)	-45	-38	kHz

Numbers in ( ) for KEKB LER

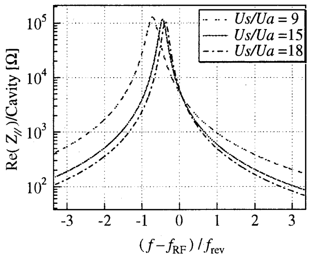

Figure 2: Coupling Impedance of the $\pi/2$ mode loaded with 9.4 A, for $U_s/U_a = 9, 15, 18$.

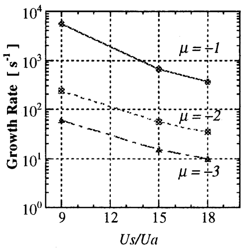

Figure 3: Growth Rates of the CBIs ($\mu = -1, -2, -3$) due to the $\pi/2$ mode, plotted as a function of U_s/U_a.

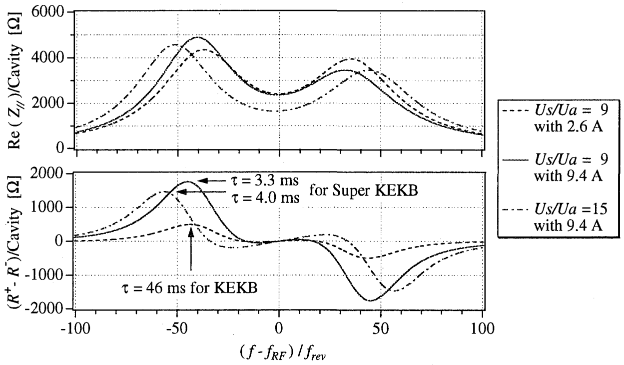

Figure 4: Coupling Impedance (top) of the 0 and π modes, and the imbalance (bottom) with respect to the RF frequency.

HIGHER ORDER MODE ISSUES

The HOM-damped structure for the ARES cavity system was carefully designed to be smoothly embedded into the whole scheme without any structural or electromagnetic incompatibility. The toughest problem was an inevitable boundary condition: two large rectangular coupling apertures at both sides of the accelerating cavity. One aperture is open to the coupling cavity, and the other to a half-cell coupling cavity for the $\pi/2$-mode termination to restore mirror symmetry for the accelerating field with respect to the vertical mid plane.

The HOM-damped structure based on ARES96 consists of four rectangular HOM waveguides (WGs) attached to the upper and lower sides of the accelerating cavity and two Grooved Beam Pipes [4] (GBPs) to both end plates, as shown in Fig. 1. The monopole and vertically polarized dipole HOMs are guided out through the HOM WGs. The extracted HOM power is guided via an E-bend in the horizontal direction and finally dissipated in two bullet-shape SiC ceramic absorbers directly water-cooled. The power capability was verified up to

3.3 kW per bullet (26.4 kW per cavity) with use of a 1.3-GHz CW klystron, but this limit was only due to the maximum power stably supplied from the klystron. The horizontally polarized dipole HOMs are guided out through the twofold GBPs with upper and lower grooves. In each groove, eight SiC tiles are arranged in a line to absorb the extracted HOM power. Each SiC tile is brazed to a water-cooled copper plate with a copper compliant layer between. The GBP HOM load was also tested, with use of the same klystron, up to 0.5 kW per groove (2.0 kW per cavity) without any significant vacuum pressure rise observed.

Figure 5 shows the WG and GBP HOM load powers per cavity plotted as a function of the KEKB LER beam current (1224 bunches with 4-bucket spacing), together with the sum of these, i.e. the total HOM power dissipation per cavity. These data are based on the calorimetric measurements for the WG and GBP loads at the downstream side with respect to the beam direction, and obtained by simply doubling the measured data owing to the mirror symmetry (see the side view in Fig. 1). Furthermore, the total HOM power and the GBP HOM power are compared with theoretical predictions shown by the solid and dashed curves, respectively. These two predictions are based on the loss factors computed with 3D-MAFIA for the following two cases: the whole damped structure (AC + 2×GBP) and the two GBPs only (2×GBP), where the bunch length $\sigma_z = 7$ mm was assumed according to other measurements. Figure 6 shows the computed loss factors plotted as a function of the bunch length, together with simulation results computed with 2D-ABCI assuming a simplified axially symmetric accelerating cell with circular beam pipes (AC + 2×CBP) instead of the GBPs. Taking into account errors in the calorimetric measurements, estimated as 10% for WG load and 13% for GBP load, the total HOM power data agrees well with the theoretical prediction. On the other hand, the excess of the measured GBP power over the prediction might be due to the mirror asymmetry of the accelerating cavity (see the front view in Fig. 1). The half-cell coupling cavity can restore mirror symmetry for the fundamental mode only.

According to the HOM power measurements and the loss factor computations, the WG and GBP HOM powers per cavity have been estimated as ~80 kW and ~20 kW, respectively, for the beam current of 9.4 A (4896 bunches with $\sigma_z = 3$ mm). Therefore, we will need to upgrade both of the WG and GBP loads, for example: to increase the number of absorbers per WG load, depending on the results of the high power testing to be resumed soon; to replace the current GBP with a winged chamber loaded with directly water-cooled SiC absorbers as shown in Fig. 7. Actually, this kind of chamber has already been developed under collaboration between the KEKB vacuum and ARES cavity groups, and several chambers have been installed to absorb the HOM power at the mask chamber sections in KEKB [5].

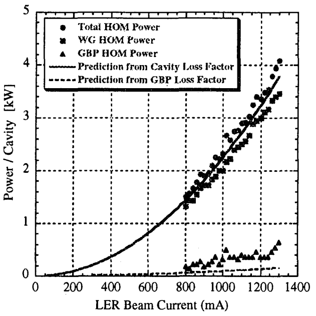

Figure 5: HOM load powers per cavity measured in the KEKB LER, compared with theoretical predictions.

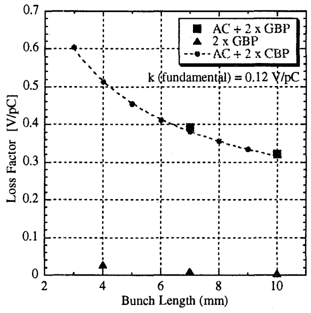

Figure 6: Loss factors computed for the whole damped structure and the GBPs only, together with those for a simplified axially symmetric strucutre with circular beam pipes (CBPs).

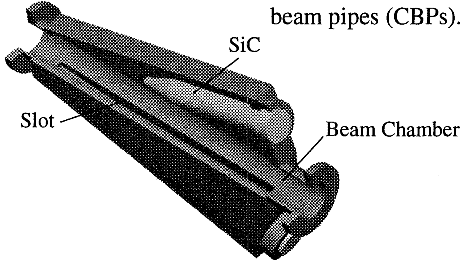

Figure 7: Winged chamber [5] loaded with directly water-cooled bullet-shape SiC abosrbers.

SUMMARY

We have investigated the growth potential or the critical limits of the ARES cavity toward Super KEKB with the LER beam current of 9.4 A. By increasing the stored energy ratio U_s/U_a from 9 to 15, the severest -1 mode of the longitudinal CBI due to the $\pi/2$ mode can be eased by one order of magnitude and down to a level with τ=1.5 ms where some RF feedback system could manage to damp it. The growth time of the CBI due to the impedance imbalance between the parasitic 0 and π modes has been estimated as τ = 4 ms, faster than that for KEKB by one order of magnitude. However, this growth time may be comparable with those expected for other HOM-driven CBI modes. Anyway, some bunch-by-bunch longitudinal feedback system will be needed. As for the HOM issues, we need to upgrade the power capabilities of the WG and GBP loads up to ~80 kW and ~20 kW per cavity, respectively. Therefore, we should first resume high-power testing for the HOM-loads, hopefully with a new klystron supplying more than 10 kW.

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