Suppression of Longitudinal Coupled-Bunch Instability using Energy Storage Cavity in B-factory RF System

Tsumoru Shintake
KEK: National Laboratory for High Energy Physics
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305 JAPAN

Abstract
The longitudinal coupled bunch instability due to the fundamental accelerating mode can to be suppressed by attaching an energy storage cavity to a normal conducting accelerating cavity. Since the stored EM-energy in this system is very large, a small frequency detuning is sufficient to compensate reactive part of the beam loading voltage induce by extreme high beam current in B-factory storage rings. In KEK B-factory case, it is possible to use a normal conducting single cell accelerating cavity connected to an energy storage cavity of 1.2 m diameter by 1.9 m length. The stored energy in this system is 8.3 Joul, and the loaded Q is 7.2×10^4. The effective impedance for the coupled bunch mode (m=-1) is reduced to as low as 18 kΩ/ring. Since the growth time of the instability is 22 msec, which is comparable to the radiation damping time, this type of instability will not occur.

I. INTRODUCTION

In B-factory storage rings[1,2], since extreme high beam current must be accumulated, the coupled-bunch instabilities become very serious problem. Instabilities are excited not only by the higher order modes(HOM) in RF-cavity, but also by the fundamental accelerating mode itself. To cure HOM problem, various type of damped cavity have been proposed. However, according to the longitudinal coupled-bunch instability due to the fundamental mode, no any realistic solution has been found out, except to use a super-conducting RF cavity with relatively higher accelerating field.

Recently, the author[3] proposed a possible solution to this problem, which uses an energy storage cavity connected to a normal conducting accelerating cavity. Due to large EM energy stored in the storage cavity, this system becomes quite stable against the longitudinal phase oscillation of the high current multi-bunch beam circulating in the storage ring. In this paper, concept of the storage cavity scheme is explained briefly, then discussions are given on problems to realize this system in practical machine, such as KEK B-factory.

II. THE STORAGE CAVITY SCHEME

An accelerating RF cavity is usually operated at off the resonance in order to compensate the reactive part of the beam loading voltage induce by the beam. In high beam current storage rings, this detuning frequency becomes quite large, and in a large storage ring it exceeds the revolution frequency of the beam. In this case, the coupled bunch synchrotron oscillation of $m\neq0$ mode is excited by the large impedance of the accelerating mode itself at the instability resonance. To eliminate this type of instability, it is essential to reduce the detuning frequency of the cavity, and also to reduce the impedance tail at the instability resonance.

We here briefly review the cavity detuning. When a beam is accelerated by the cavity voltage it induces a beam loading current in the rf cavity as its reaction. In electron or positron storage rings, in order to insure stability against phase oscillation the beam is accelerated at off the crest of the accelerating voltage. Therefore, the beam current I_b is out of phase ϕ with the beam accelerating voltage, where ϕ is called the synchronous phase. The real part of the beam loading power, $\mathrm{Re}(1/2V_cI_b^*) = 1/2V_cI_b\cos\phi$, is the time average of the net energy transfer utilized for beam acceleration. On the other hand, the imaginary part, $1/2V_cI_b\sin\phi$, is the reactive beam loading power, which can not be utilized for beam acceleration, and reflects back to the rf generator. Finally, it reduces the system power efficiency. In order to reduce this reflection power and to minimize the required generator power, the rf-cavity resonance is generally detuned from the generator frequency, and the imaginary part is compensated by bypassing through the resonator. The compensating condition is

$$j\omega CV_c + \frac{V_c}{j\omega L} = I_b\sin\phi. \qquad (1)$$

Thus the detuning frequency required for compensation is

$$\frac{\Delta\omega}{\omega_0} = \frac{I_b\sin\phi}{2\omega_0 CV_c} = \frac{\mathrm{Im}(\frac{1}{2}V_cI_b^*)}{2\omega_0 W_0}, \qquad (2)$$

where W_0 is the energy stored in the cavity. This equation implies that the required frequency detuning is equal to the reactive energy flow per one cycle to the stored energy inside the cavity. Therefore, in order to minimize the frequency detuning we need to increase the stored energy.

For this purpose, here we introduce an energy storage cavity connected to a conventional single cell accelerating cavity as shown in Fig. 1. If the coupling between two cavities is sufficient, the electrical performances of total system become;

$$(R/Q)_{tot} = \frac{W_A}{W_{tot}}(R/Q)_A, \qquad (3)$$

$$\Delta f_{tot} = \Delta f_A\cdot\frac{W_A}{W_{tot}} \qquad (4)$$

$$Q_{tot} = \omega_0\frac{W_{tot}}{P_{tot}} \qquad (5)$$

$$R_{tot} = \frac{R_A}{1 + P_S/P_A} \quad (6)$$

where the subscripts A, S and tot. represent the accelerating cavity, the storage cavity and the total system, respectively. Since we use a large volume storage cavity, it is easy to store a large amount of EM energy. Therefore as known by eqs. (3) and (4) the R/Q parameter of this system becomes much smaller than that in the case of only the accelerating cavity is used, and the detuning frequency for the beam loading compensation becomes very small. If we use a low loss mode in the storage cavity, the total wall dissipation power does not increase so much, and this system shows quite high Q factors as indicated by eq. (5). Both small frequency detuning and a high Q-factor are very important to reduce and cancel out the impedance tails at the instability resonances. Therefore the present scheme can be one of the best solution to cure the multi-bunch longitudinal instability due to the fundamental accelerating mode. Since the shunt impedance of this system: eq. (6), is not degraded so much, we can operate this system with reasonable RF input power.

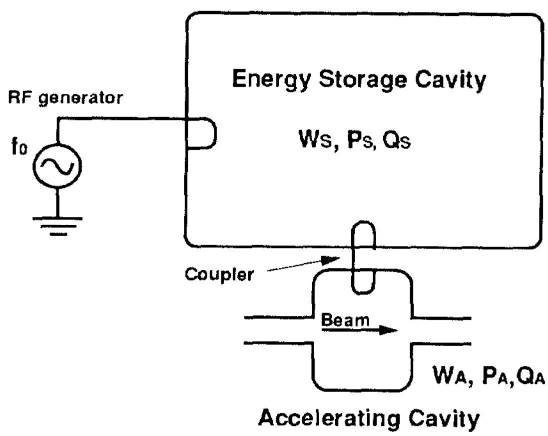

Fig.1 An accelerating cavity connected to an energy storage cavity.

III. APPLICATION TO THE KEK B-FACTORY

In the KEK B-factory, we need to store a beam current of 2.6 amperes in the low-energy ring, and 1.1 amperes in the high energy ring in order to achieve the maximum design luminosity of 1 x $10^{34}cm^{-2}sec^{-1}$. Since the coupled bunch instability problem is more severe in the low-energy ring than the high-energy ring, we discuss here only the low-energy ring case. The principal machine parameters are listed in Table 1. We assumed the maximum capable wall-dissipation power per one-cell of the accelerating cavity to be 60 kW. Then the cavity voltage becomes 0.6 MV per cell and 22.2 MV per ring.

We use low loss mode of TE015 in the storage cavity. Such mode has been successfully used as a high-power storage cavity in an rf-pulse compressor system of SLED at S-band frequency. The cavity dimensions at 508 MHz become a length of 1.9 m and a diameter of 1.2 m. The unladed Q-value is 2.6 x 10^5. We connect this storage cavity to a conventional accelerating cavity as shown in Fig. 2. We assumed a single cell pillbox type accelerating cavity, which has a HOM damping structure of "Choke Mode Cavity"[4]. The shunt impedance of this cavity without connecting to the storage cavity is 6.3 MΩ/cell, which includes a degradation of -25% due to the wall dissipation power in the choke HOM damping structure.

The field intensity ratio: HS/HA between the storage cavity and the accelerating cavity is a free parameter. If we increase the field intensity in the storage cavity, we can store larger energy, but the wall dissipation power in the storage cavity becomes large. On the other hand, if we choose the field intensity in the storage cavity to be low, the total stored energy becomes small, as a results the detuning frequency becomes large again and the instability will occur. Here we choose the field intensity ratio at 0.5. Electrical performance of this system is summarized in Table 2. The total stored energy is 8.3 Joul, which is twelve time larger than that in the case of using only the accelerating cavity. As a consequence, the detuning frequency is only - 15 kHz at the maximum beam current of 2.6 amperes, which is much smaller than the beam revolution frequency of 99.3 kHz. The system has a very high loaded-Q of 7.2 x 10^4, this is comparable parameter with that in a super conducting cavity system. Because of this high Q-factor and the small frequency detuning, the impedance tail becomes very small and the impedance cancellation works well between the damping and anti-damping mode, finally the effective impedance for the coupled-bunch mode of m=−1 becomes 18 kΩ/ring. Since the growth time of the instability is 22 msec, and this is comparable to the radiation damping time, this type of instability will not occur.

IV. DISCUSSION AND CONCLUSIONS

A. Cure of parasitic coupled resonator modes.

Since the proposed system is a kind of coupled resonator, it is inherent to have multiple resonances according to the number of cavities. Two-cavity-coupled system shows two different modes(zero and π) according to the phase difference between the two cavities. If we use the π-mode for beam acceleration, another zero-mode will appear near to the accelerating frequency, and may cause the same instability. To cure this parasitic mode is therefore a key issue in using this type of coupled cavity system.

Recently, Y. Yamazaki and T. Kageyama[5] proposed a scheme of a three-cavity system to solve this problem. They introduced a coupler cavity between the accelerating and the storage cavity. The π/2 mode is used for beam acceleration. The parasitic impedance of zero and π-modes are effectively damped by a coupler installed in the coupling cavity, while minimal effect on the accelerating cavity. At the same time, since the impedance distributions of zero and π mode are almost symmetry around the accelerating π/2 mode, the impedance cancellation will work well between two parasitic modes. As a consequence, the residual impedance due to the parasitic mode can be made lower than the instability thresholds of $R_+ - R_- < 290$ Ω/cavity.

B. Cure of the higher order modes in the accelerating cavity.

The choke mode cavity[4] will be one of the most suitable structure to effectively damp all of the higher order modes in the accelerating cavity. It is possible to achieve damped Q-value of less than 10 for the most dangerous mode of TM110 by optimizing the choke structure[6]. Since the choke mode cavity has perfect cylindrical symmetry, the heat density of wall power dissipation is very uniform and there is no heat concentration at any point. Therefore, we may apply higher acceleration voltage per cell, and reduce the total number of cavity around the ring. This is an important factor to reduce the instability impedance for both of the higher order modes and the fundamental mode. The total TM011 mode impedance is 50 kΩ/m/ring.

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TABLE 1:
Principal Machine Parameter of KEK B-factory
(low energy ring)

Beam Energy	E	3.5	GeV
Beam Current	I_0	2.6	A
Revolution Frequency	f_{rev}	99.3	kHz
RF frequency	f_0	508.6	MHz
Total Cavity Voltage		22	MV
Energy Loss per Turn		0.95	MV
Synchronous Phase	ϕ	87.5	deg.
Synchrotron Frequency	f_s	6.9	kHz
Cavity Voltage	V_c	0.6	MV/cell
Number of Cells		37	

TABLE 2 : Performance of
the Storage Cavity Coupled System

Stored Energy / unit			
in accelerating cavity	W_A	0.68	Joul
in storage cavity	W_S	7.6	Joul
in total system.	W_{tot}	8.3	Joul
Wall Dissipation Power / unit			
in accelerating cavity	P_A	57	kW
in storage cavity	P_S	93	kW
Beam acceleration power	P_b	67	kW
Input RF-power / unit	P_{in}	217	kW
Shunt Impedance	R_{tot}	2.4	MΩ/cell
	$(R/Q)_{tot}$	13.6	Ω / cell
Unloaded-Q	Q_{tot}	1.76×10^5	
Optimum Coupling	β_0	1.45	
Loaded-Q	Q_L	7.2×10^4	
Detuning Frequency	Δf	− 15	kHz
Effective Impedance			
for the coupled-bunch mode(m = −1)			
	$R^+ - R^-$	18.0	kΩ / ring
Growth Time of the Instability		22	msec

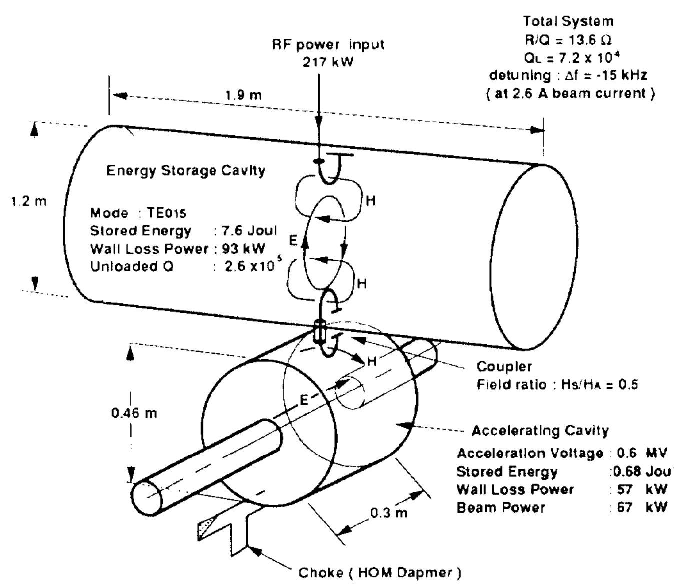

Fig. 2 Proposed accelerating rf cavity for KEK B-factory.