HIGHER HARMONICS BEAM LOADING COMPENSATION FOR A BROAD BAND MA-LOADED RF CAVITY

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Abstract

A broad band RF cavity loaded with magnetic alloy cores has been developed for the Japanese Hadron Facility synchrotrons. Its Q-value can be chosen at between 0.5 and 5. To reduce transient beam loading effects, a small Q-value (< 3) is preferable to shorten the transient period. However, the circulating beam current of up to 7 A will induce a spurious voltage at the accelerating gap, which deforms the gap voltage due to higher harmonics components, if the Q-value is less than 3. The resulting RF-bucket distortion may cause the beam loss. Therefore we have designed a beam loading compensation system to suppress the higher harmonics components.

1 INTRODUCTION

The accelerator complex of JHF (Japanese Hadron Facility) consists of a 200 MeV linac, 3 GeV booster ring and 50 GeV main ring [1]. The accelerating voltage required for the booster ring is 420 kV, and that for the main ring is 280 kV. The operating RF frequency ranges are 2 - 3.4 MHz and 3.4 - 3.5 MHz for the booster and main rings, respectively. The maximum circulating beam current is 7 A in both synchrotrons. Because of the limited space in the tunnel, the accelerating gradient as high as possible (> 15 kV/m) should be required for RF cavities. With conventional ferrite-loaded RF cavities, it is difficult to get such a high accelerating gradient, because of undesirable degradation of the shunt impedance under the high RF magnetic field and the resulting huge heat load. We have therefore developed an RF cavity loaded with magnetic alloy (MA) cores having a high saturation magnetic flux density and a high Curie temperature, such as Fe-based nano-crystalline FINEMET cores. The shunt impedance was kept constant at a sufficient value even under a high RF magnetic field of more than 1 kG. The RF properties were quite stable, even when the surface temperature rose to 150 °C [2].

Another important feature of the MA cores is their low Q-values of 0.5 - 5. The Q-value can be changed without large degradation of the shunt impedance by adjusting the height of radial gaps installed in the toroidal core. The MA-loaded RF cavity offers several advantages. First of all, the periodic transient beam loading effects during an injection process in the main ring can be mitigated, especially in the case of the Q-value of less than 3 [3]. Because the transient period is short enough for individual bunches to be affected by their own wakefield only (single bunch effect), the individual bunches initiate a same synchrotron oscillation which can be easily damped with $\Delta\phi$ feedback loop. The 30 kW test cavity [4] demonstrated that the operation over the frequency range of 2 - 3.5 MHz was possible without the cavity tuning loop. The RF control system therefore becomes simple and its stable operation against beam loading instability becomes easy [5]. The coupled bunch instability due to the fundamental and parasitic resonances is another significant instability. The low Q-value of MA cores is also effective to damp the coupled bunch instability [6]. The MA-loaded cavity is also suitable for barrier bucket operation [7] because of the power saving characteristics.

On the other hand, a new problem arises in the broad band RF cavity, if the Q-value is less than 3. It is a beam loading effect due to higher harmonics induced by rigidly bunched beams. The bunching factor becomes less than 0.1 in the acceleration process of the main ring. The resulting RF-bucket distortion may cause longitudinal emittance growth and lead to beam loss. However, a new type of high-gradient (HG) RF cavity, which can realize stable operation with a low shunt impedance, has been successfully operated in a preliminary test [8]. It is expected to mitigate the beam loading effect including that due to higher harmonics. In this paper, the higher harmonics beam loading effect is evaluated in section 2. The compensation system to suppress it is presented in section 3.

2 HIGHER HARMONICS BEAM LOADING

If the Q-value of the cavity is less than 3, the motion of beam particles in the longitudinal phase space is affected by the amplitude and phase of gap voltage at the n-th harmonic of the RF frequency, V_n and θ_n . They can be expressed by phasor form V_n^* and calculated from the cavity impedance Z_n^* and current I_n^* by a complex representation as

$$\begin{aligned} V_n^* &= V_n e^{j\theta_n} = V_{n,\,rf}^* + V_{n,\,b}^* + V_{n,\,sc}^* \\ &= Z_n^* \left(I_{n,\,rf}^* + I_{n,\,b}^* \right) + V_{n,\,sc}^* \end{aligned} \qquad (1)$$

where $I_{n,rf}^*$ and $I_{n,b}^*$ are the n-th harmonic currents supplied with the RF power source and induced by the bunched beam, respectively. Space charge effects $V_{n,sc}^*$

are negligible at 50 GeV. The gap voltage induced by the bunched beam $V_{n,b}^*$ decelerates the bunch center and defocuses the beam. The deceleration of the bunch center is automatically compensated for by phase shift of the bunch center to the acceleration phase of $V_{1,rf}^*$, because the RF control system works stably. However, the defocusing due to RF-bucket distortion may cause nonlinear motion of beam particles and longitudinal emittance growth.

We evaluated the beam loading for the main ring. Figure 1 shows the calculated spectra of the circulating beam currents for bunching factors of 0.05 (at extraction) and 0.3 (at injection), assuming parabolic distribution of the beam intensity in a bunch. Because one bucket out of 17 is empty for the fast extraction, the frequency component is a discrete line spectrum with line spacing of the revolution frequency 200 kHz, although the harmonics of the fundamental RF frequency are dominant. When the bunching factor becomes less than 0.1, the intensities of the harmonic currents up to the third one are about two times as large as the average circulating beam current of 7 A.

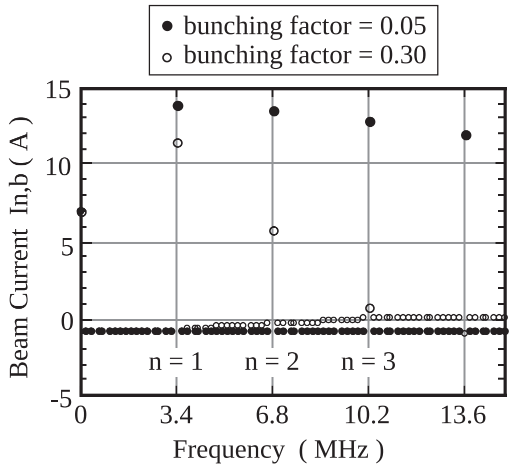

Fig. 1 Calculated Beam Current Spectra

Figure 2 shows the relation between the relative loading ratio $Y_n = V_{n,b} / V_1$ and the bunching factor for the individual harmonics. The total shunt impedance and the Q-value of the RF acceleration system including the RF power source are assumed to be 5 kΩ and 0.5, respectively. The HG RF cavities loaded with MA cores, directly cooled by pure water, can realize the total accelerating voltage V_1 of 280 kV with the total shunt impedance of only 5 kΩ. The relative loading ratio at the fundamental RF frequency Y_1 is reduced to 0.3, which should make the RF control system work stably. Beam loading effect due to the higher harmonics should also be mitigated, because the relative loading ratios Y_n ($n > 1$) are less than 0.2 even at the bunching factor of 0.05. Figure 3 illustrates the RF-bucket distortion at the bunching factor of 0.05. The dotted line shows the Hamiltonian constant line which just includes the beam emittance in the case without the RF-bucket distortion. When the Q-value is 2, the RF-bucket distortion is little and the resulting emittance growth will be small. Multi-particle tracking simulations [3] also show that the emittance growth is small even without any compensation, if the Q-value is higher than 3 .

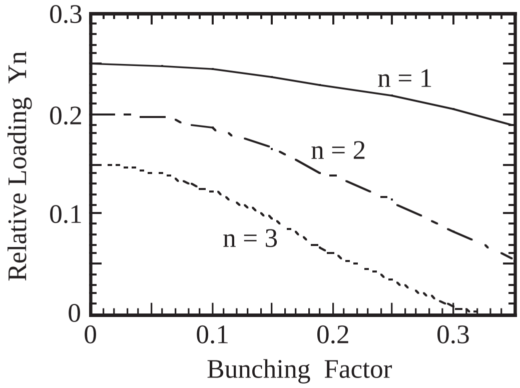

Fig. 2 Higher Harmonics Beam Loading

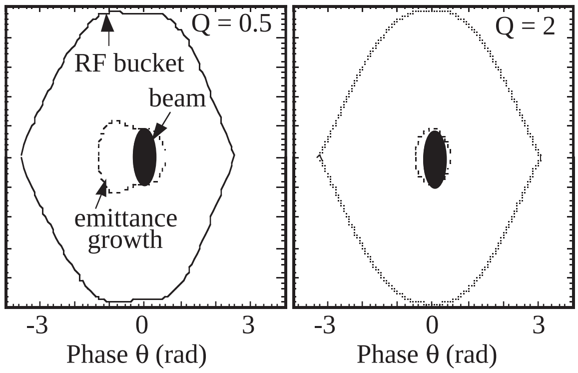

Fig. 3 RF-bucket Distortion

3 COMPENSATION SYSTEM

In principle, the beam loading effect can be canceled completely by an additional current supplied with the RF power source to meet the condition $I^a_{n,rf}{}^* = - I_{n,b}^*$. Of course, a large reactive power is required for the RF power source to supply the additional current. The reactive power is dissipated in the plates of high-power tubes such as 150 - 300 kW class tetrodes. From the viewpoint of the scale of the RF power source, beam loading compensation up to the third harmonic is effective.

There are two schemes to generate the compensation current $- I_{n,b}^*$. One is the feedforward method. A pick-up signal of the circulating beam current is added to RF reference signal in the low-level RF control system so that the pick-up signal can cancel the beam-induced current at the cavity. The other is the RF-feedback method. A portion of the gap voltage is fed back to the low-level RF control system so that the pick-up signal can reduce the gap voltage. The direct RF feedback around the cavity is not applicable to the beam loading compensation up to the third harmonic, because of the phase lag of the loop with a total path length of at least 10 m. If the bandwidth of the feedforward / RF-feedback loop is wide enough to neglect the frequency-dependence of the delay time of the loop, the one-turn delay method with a variable delay is useful. However, it is difficult to widen the bandwidth of the control-grid circuit of 150 - 300 kW class tetrode RF amplifier. The cut-off frequency lies around the second harmonic frequency without a special matching network. Besides, the bandwidth of the cavity impedance is also finite.

Therefore, it is better to adopt a feedforward / RF-feedback system with a parallel comb filter, in which a feedforward / RF-feedback paths are separately constructed for individual harmonic signals. In each path, the amplitude and phase of the signal can be adjusted independently. Narrow band filters with Q-value of at least 15-20 are used to separate the signal picked up with a beam monitor or a gap voltage monitor into each harmonic signal. The cavity impedance seen by the circulating beam is then much reduced at the harmonic frequencies. Attention must be paid to setting the center frequencies of the filters just at the corresponding harmonic frequencies, otherwise coupled bunch instability might be excited. It is untractable to sweep the center frequencies of the filters to accord with the harmonic frequencies moving in a synchrotron operation cycle. Therefore, each harmonic component should be once converted to a signal with a fixed frequency, at which filtering, amplitude and phase adjustment are performed.

Figure 4 shows the block diagram of a feedforward / RF-feedback system with a parallel comb filter. Because 70 MHz is selected as the fixed frequency, the image frequency to be removed lies above 140 MHz. Considering the bunching factor, the frequency component higher than 140 MHz is negligible and can be attenuated easily with a low-pass filter of 20 MHz if necessary. Special image-rejection mixers are not necessary for the input mixers. Besides, the undesired upper sideband generated by the output mixers lies above 140 MHz, which can be attenuated easily with a low-pass filter of 20 MHz. Even if the attenuation is insufficient, the RF amplifier has little gain for it. Special single sideband mixers are not necessary for the output mixers. It is a certain way to avoid the coupled bunch instability, to design the bandwidth of the band-pass filters to be narrow enough not to affect the impedance at the neighboring sidebands one revolution frequency away from the harmonic frequencies, although the response of the feedforward / RF-feedback system becomes worse.

For the main ring, the bandwidth is set at 40 kHz (± 20 kHz) for the second and third harmonics. The resulting response time is about 18 μs, namely a 3.5-turn delay, which is comparable to delays of slow-feedback techniques such as $\Delta\phi$ and AVC (ALC) loops. On the other hand, the bandwidth is set at 140 kHz (± 70 kHz) for the fundamental RF frequency to realize a fast feedforward / RF-feedback of 5 μs (one-turn) delay. For the booster ring, the minimum revolution frequency is 500 kHz. The bandwidth for second and third harmonics can be widened to 100 kHz (± 50 kHz). The maximum response time is about 7 μs, namely a 6-turn delay. However, the bandwidth for the fundamental RF frequency cannot be widened further, to separate the harmonic components at the minimum RF frequency of 2 MHz. The maximum response time is then 5 μs, namely a 4.3-turn delay. Because the synchrotron frequency is lower than 7 kHz, the impedance at the synchrotron sidebands can be much reduced. For the booster ring in which the RF frequency sweeps over a wide range, the RF-feedback method seems to be preferable, because the precision required for amplitude and phase adjustment is not so high, although a complete compensation is not possible.

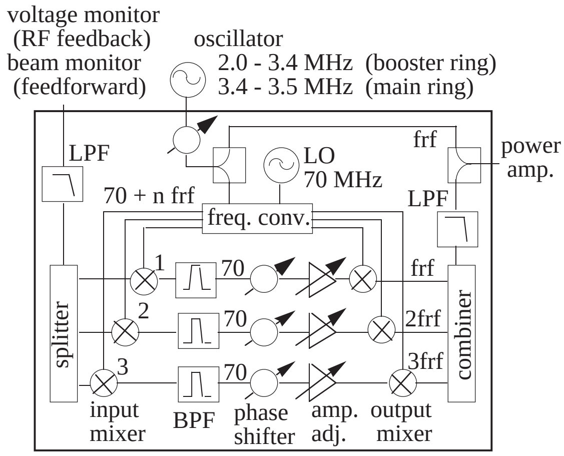

Fig. 4 Beam Loading Compensation System

The compensation system shown in Fig. 4 is not a final. We are also trying to design it without the frequency-conversion to a fixed frequency.

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