BEAM LOADING EFFECTS IN JHF SYNCHROTRON

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Abstract

Beam loading effects on the rf system of JHF proton synchrotrons have been investigated by both computer simulation and experiment using a low energy electron beam. From the simulation results, it is found that even under the heavy beam loading the beam acceleration becomes stable if applying the beam loading compensation, and the compensation experiment is succeeded on proto-type Magnetic Alloy loaded cavity.

1 INTRODUCTION

In the JHF(Japan Hadron Facility) proton synchrotron [1], beam loadings are severe problems for the rf acceleration because its circulating beam current is high($\sim$7 A). A high gradient MA(Magnetic Alloy [2, 3])-loaded cavity [4, 5] has been developed and achieved high accelerating field gradient of more than 2.5 kV per core of 2.5 cm thickness [5].

This type of rf cavity is useful to suppress the coupled bunch instability [6] because its quality factor is low(Q:1 $\sim$ 5). On the other hand, the beam induced voltage is composed of both fundamental frequency and higher harmonics, although a ferrite-loaded cavity has only fundamental component because its quality factor is high(mostly, Q:10 $\sim$ 30).

In order to investigate the beam loading effects on the high gradient MA-loaded cavity theoreticically and experimentally, we have developed a simulation code of the longitudinal motion, and we have constructed a beam loading test bench.

2 SIMULATION

We have developed a multi-particle simulation code in the longitudinal phase space, which includes the space charge, $\Delta\phi$-feedback with the DC-coupled method and compensation of the beam induced voltage.

The beam induced voltage is obtained with a frequency/time domain mixed calculation [8]. The space charge effect in the longitudinal motion is calculated by the following formula,

$$V_{\rm spc} = \frac{e^2 g}{4\pi\varepsilon_0(\beta\gamma c)^2\beta}\frac{dI_{\rm b}}{dt}, \qquad (1)$$

where g is a geometrical factor.

The total voltage per turn V becomes,

$$V = V_{\rm gap} + V_{\rm spc} = V_{\rm g} + V_{\rm b} + V_{\rm spc}. \qquad (2)$$

Using V, a synchrotron motion is presented as following equations,

$$(\delta E)_{\rm turn} = qV(\phi) - qV_0(\phi_{\rm s}) \qquad (3)$$

$$(\delta\phi)_{\rm turn} = -2\pi h\eta\frac{\Delta p}{p} + \Delta\phi, \qquad (4)$$

where V_0 is a nominal accelerating voltage, $\Delta\phi = \phi_{\rm b} - \phi_{\rm gap}$ is a feedback phase value by the $\Delta\phi$-feedback, $\phi_{\rm b}$ and $\phi_{\rm gap}$ are the phase of the bunch center and that of the gap voltage, respectively.

2.1 Periodic Transient

In the JHF 50 GeV Main Ring, sixteen bunches are injected from the 3 GeV Booster Ring four by four in each Booster Ring cycle although its harmonic number is 17, and therefore there is an empty bucket during an acceleration, so the beam has many harmonics of the revolution frequency. It causes periodic transient effect and it becomes the maximum when eight bunches are injected.

Since the MA-loaded cavity has a low Q Value, a wake field caused by a bunch affects on the bunch itself larger than that of a high Q cavity. However, the wake field damps quickly, so the effect on the next bunch is very small. In this case, even the trasient effect becomes only a single bunch problem, while the transient effect is a multi-bunch effect in the high Q cavity because the wake field damps slowly.

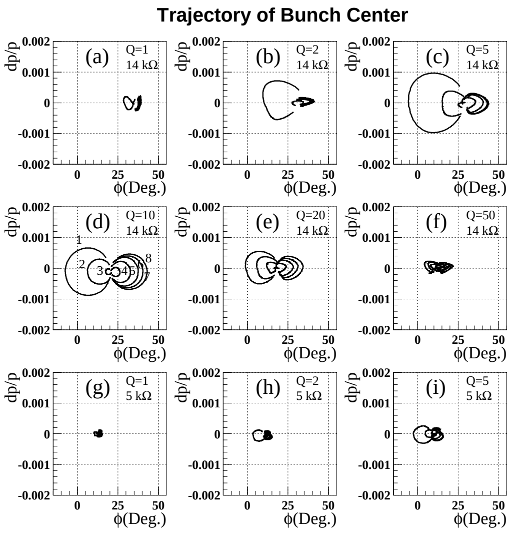

Figure 1: Trajectory of the bunch center in the longitudinal phase space.

Figure 1 (a)-(f) show the Q-dependece of the transient effects. Beam intensity is same in all Q value, 1.25×10^{13} particles per bunch, and shunt impedance is 14 kΩ.

In Fig. 1, each line shows a trajectory of a bunch center in the longitudinal phase space. Vertical axis and horizontal axis are momentum difference and the phase measured from the nominal synchronous particle, respectively, which is free from any beam loading.

As shown in Fig. 1(a)-(f), each bunch center is oscillated apart from a locked phase of the $\Delta\phi$-feedback by the transient effect. Increasing Q up to 10, the oscillation of each bunch center becomes larger, and increasing Q further, the oscillation becomes smaller again. The transient effect is most severe around $Q = 10$. On the other hand, in the low Q case the transient effect is very small(see Fig. 1(a)). Especially in the case of high gradient MA-loaded cavity as shown in Fig. 1(g)-(i), it is very small even with the $Q = 5$, and it is interesting the effect is smaller than very high Q case. This is the advantage of the MA-loaded cavity.

2.2 Bucket Distortion

Simulation results of the potential well distortion at the injection in the JHF 50 GeV Main Ring had been already reported [7, 8]. The results at the extraction will be described in this paper. Since the bunching factor becomes 0.038, a peak circulating current reaches about 180 A. We simulate in the case that the cavity impedance is 5 kΩ(high gradient MA-loaded cavity). An initial beam emittance is shown in Fig. 2.

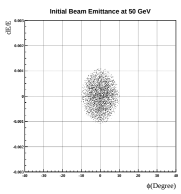

Figure 2: Initial beam emittance.

Figure 3 shows the beam emittances in the longitudinal phase space after 10,000 turns(48.21 msec.) in the case of $Q = 1$, 3 and 5. The compensation of the beam loading [9] up to 3rd harmonics is applied in the case of $Q = 1$(Fig. 3(a)), where the compensating voltage is obtained from the Fourier analyzed amplitudes and phases of the beam induced voltages by integrating up to the the 3rd harmonics.

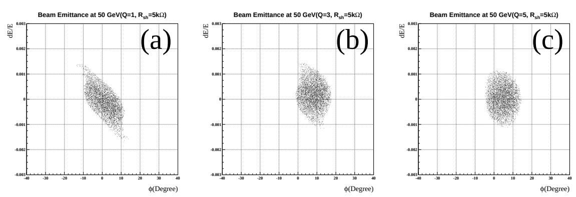

Figure 3: Beam emittance in the longitudinal phase at the extraction.

The simulation results show that all particles still remain in the rf bucket, although the beam emittance is slightly collapsed and the filamentation occurs. In the case of $Q = 1$, the bunch length becomes two times larger than an initial bunch length, since quadrupole motion caused by the higher harmonics is very large even with the beam loading compensation. In the case of $Q = 3$ and 5, the quadrupole motion is relieved without the compensation, so the quality factor of three or more is needed to suppress the quadrupole motion. However, there is a posibility to suppress the quadrupole motion by using the AVC loop, and if the bunching factor becomes slightly larger than the designed value during the acceleration, then the quadrupole motion will be settled. They should be investigated.

3 BEAM LOADING COMPENSATION TEST

In order to investigate the feasibility for the compensation of the beam induced voltage, we have constructed a beam loading test bench. A high intensity electron beam can be injected into a proto-type MA loaded cavity. A schematic setup is shown in Fig. 4.

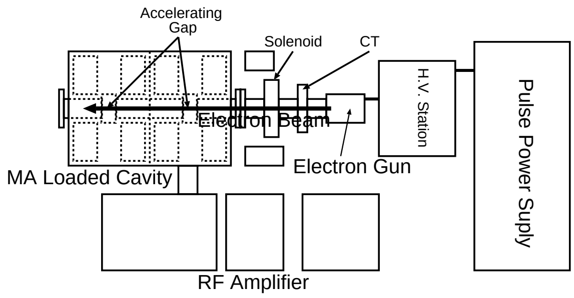

Figure 4: Schematic view of the test bench.

Bunch-train(5 μsec.) modulated by 3 MHz is generated by a thermionic gun using EIMAC Y-796 grid-cathod assembly, and accelerated by a high voltage pulse. The bunch width is changed by width of grid pulse. A wide band current transformer(100 kHz$\sim$1 GHZ) is set at the upper stream of the cavity to measure the beam current. The current operation parameters of the electron gun are shown in Table 1.

Electron Energy	$\sim$ 175 keV
Peak Current	$\sim$ 4.8 A
Bunch Width	70 $\sim$ 130 nsec.
Bunch Interval	300 nsec.
Number of Bunch	16

Table 1: The operation parameters of the electron-gun.

The compensation of the beam loading is tested in this test bench. A schematic setup of the compensation is shown in Fig. 5.

The beam signal picked up by the current transformer is atteneuted and delayed by cable delay line arbitrary, then fed into the cavity through amplifiers. When the atteneution and delay can be optimized, the beam induced voltage is compensated clearly. In this compensation test, the beam induced voltage is picked up by high voltage probes(1:1000) at the cavity gap, and we adjust the atteneution and delay to make the induced voltage minimize. The compensation is done in one bunch delay(300 nsec.).

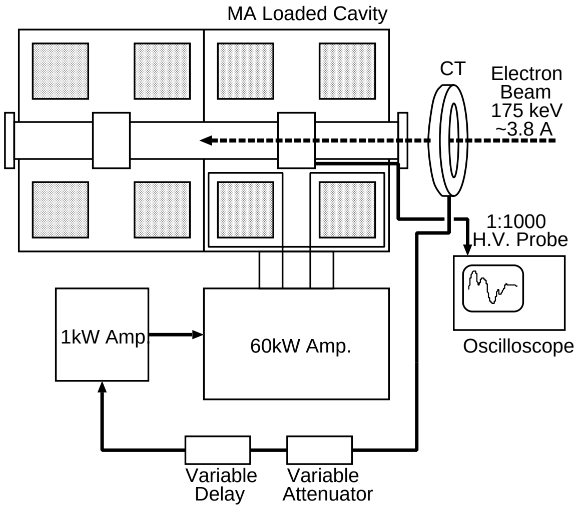

Figure 5: Setup of the compensation test.

The measured spectrums of the cavity gap voltage are shown in Fig. 6. White bar is the spectrum without compensation, and black one is the spectrum with compensation. As clearly seen in Fig. 6, the fundamental component of the gap voltage is significantly decreased about one thirtieth, and higer harmonic components are also decreased about one half. Further study using a filtering method is planned to compensate the higer harmonics effectively.

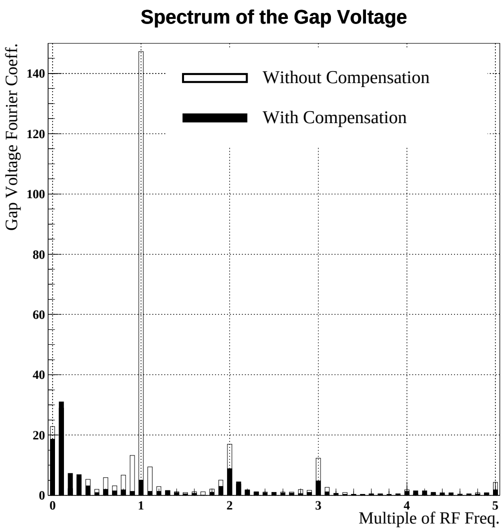

Figure 6: Spectrum of the gap voltage.

4 SUMMARY

We evaluated the transient beam loading effects by the multi-particle simulation code, and it was found the periodic transient effects did not appear in the MA-loaded cavity because of its low Q factor.

At the extraction in the JHF 50 GeV Main Ring, the peak circulating current becomes very high due to the small bunching factor. To manage the transient and the bucket distortion problems, the quality factor of 3∼5 seems to be an optimum solution. However these effects can be compensated by feedback/feed-forward techniques for both $Q \geq 5$ and $Q \leq 3$ cases on the MA-loaded cavity.

In the test of beam loading compensation by an electron beam, the beam induced voltage could be compensated on the MA-loaded cavity. To decrease the higher harmonics effectively, the compensation test with filtering will be done. Further, in order to investigate the feasibility of this compensation scheme to the ring operation, the analysis included characteristics of amplifiers, circuits, delays will be done.

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