Beam Loading in JHF 50 GeV Proton Synchrotron

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Abstract

Longitudinal particle motion in JHF 50 GeV proton synchrotron have been investigated by computer simulation. We found that emittance blow up was not so serious even without a beam loading compensation at the present design intensity, but more stable operation becomes possible applying the fundamental and 2nd harmonic rf mode compensation.

1 Introduction

In JHF(Japan Hadron Facility) proton synchrotron [1], heavy beam loading of rf system is a very severe problem in rf acceleration because its circulating beam current is large (Average beam current is 7 A in 50 GeV main ring). The broad band rf cavity [2, 3] loaded new magnetic alloy material(MA rf cavity), 'FINEMET', [4] has been developed and achieved high accelerating voltage of more than 10 kV/m.

This type of rf cavity is useful to suppress the coupled bunch instability [5] because its quality factor is low($Q \sim 1$). But, on the other hand, the beam induced voltage is composed of not only fundamental but also higher order components of the wake field, contrary to the ferrite loaded rf cavity which only fundamental component is dominant because its quality factor is high(mostly, $Q > 10$).

We have developed a simulation code of the longitudinal motion to investigate the feasibility of the beam induced voltage compensation.

2 Beam Loading Simulation

The beam induced voltage is obtained with a frequency domain calculation.

$$V_{\mathrm{b}}(\omega) = Z_{\mathrm{cav}}(\omega) \times I_{\mathrm{b}}(\omega), \tag{1}$$

where $V_{\mathrm{b}}(\omega)$ is the beam induced voltage on the frequency ω component, I_{b} is the beam current on the frequency ω component, and $Z_{\mathrm{cav}}(\omega)$ is an impedance of the rf cavity.

In eq.(1), $I_{\mathrm{b}}(\omega)$ is obtained by a Fourier transformation based on a revolution frequency. The cavity impedance $Z_{\mathrm{cav}}(\omega)$ is obtained from LCR parallel resonant circuit. Assuming a peak value of a shunt impedance of 500 Ω per cavity, the magnitude of the impedance $|Z|$ is shown in Fig. 1 for various Q values.

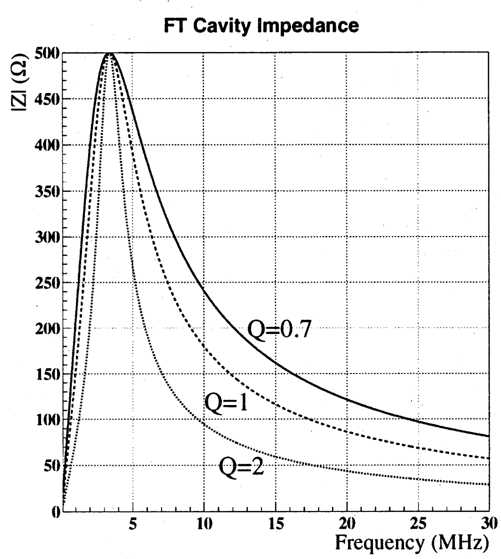

Figure 1: The impedance of the broad band rf cavity.

There are seven rf stations each of which consists of four cavities are installed in the 50 GeV main ring. The total impedance seen by the beam is 14 kΩ.

The beam induced voltage $V_{\mathrm{b}}(\omega)$ in eq. (1) is transformed to the time domain voltage $V_{\mathrm{b}}(t)$ through an inverse Fourier transformation.

$$V_{\mathrm{b}}(t) = \sum_{N} V_{\mathrm{b}}(N\omega_{\mathrm{rev}}) e^{-iN\omega_{\mathrm{rev}}t} \tag{2}$$
$$(N = 1, 2, 3, \cdots)$$

Then, an accelerating voltage V_{acc} is,

$$V_{\mathrm{acc}} = V_{\mathrm{g}} + V_{\mathrm{b}}, \tag{3}$$

where V_{g} is the voltage of an rf power amplifier.

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Using V_{acc}, the synchrotron motion is presented as following equations,

$$(\delta E)_{\mathrm{turn}} = qV_{\mathrm{acc}}(\phi) - qV_{\mathrm{g}}(\phi_{\mathrm{s}}) \tag{4}$$

$$(\delta\phi)_{\mathrm{turn}} = -2\pi h\eta\frac{\Delta p}{p}, \tag{5}$$

The following parameters are used in this simulation.

Ring circumference	1445 m
Amp. generating voltage V_{g}	280 kV
Harmonic number	17
Initial revolution frequency	201.5 kHz
Initial energy	3 GeV
Initial $\Delta p/p$	$\pm$ 0.4 %
Initial bunch length	120 nsec.
Bunch shape	parabolla
Synchronous phase	0 Deg.
Momentum compaction factor α_{p}	-0.001
Number of particle per bunch	1.25×10^{13}

Table 1: JHF 50 GeV main ring parameters.

The number of the macro particle in the simulation was 5000 per bunch.

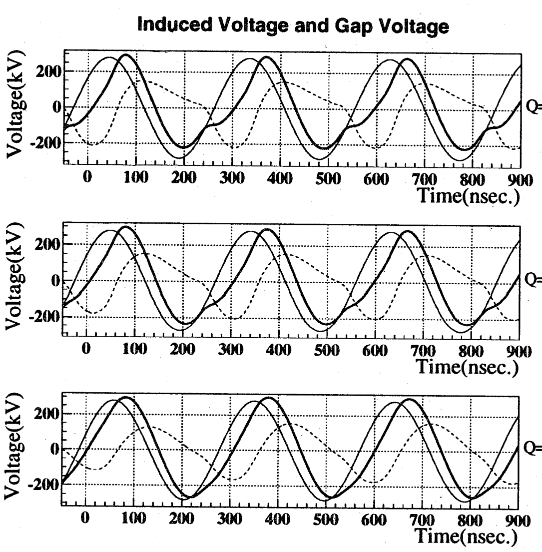

Figure 2: Accelerating voltage shift caused by the beam induced voltage.

The Figure 2 shows how the beam induced voltage(dot line) affects the gap voltage(thin solid line), and the phase of the gap voltage is shifted. As shown in Fig. 2, the beam induced voltage reachs 220 kV, 200 kV and 180 kV in case of $Q = 0.7$, $Q = 1$ and $Q = 2$, respectively. The larger quality factor brings the smaller beam induced voltage.

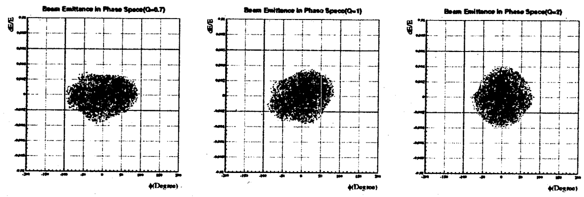

Figure 3: Beam emittance in a phase space after 1000 turns under the beam loading.

The Figure 3 shows a beam emittance in a phase space(dE/E-ϕ plain) after 1000 turns(4.47 msec.). Even under the beam loading all particles still remain in the rf bucket, but the beam emittance is slightly collapsed for the lower quality factor.

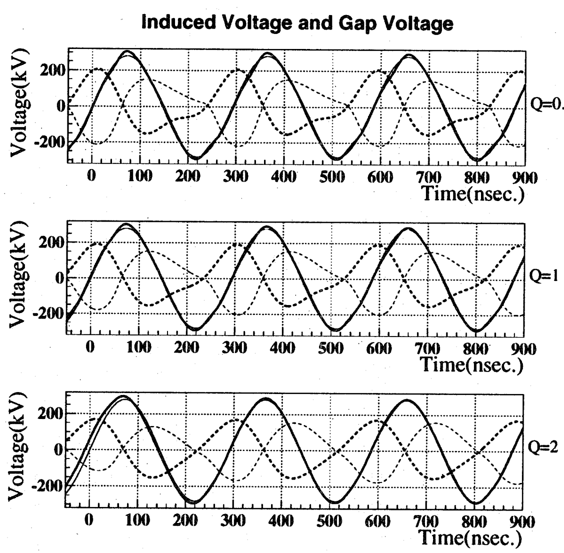

Figure 4: The Compensating voltage for the beam induced voltage.

The thick dot lines in Fig. 4 are the compensating voltages. The compensating voltage is obtained from the Fourier analyzed amplitudes and phases of the beam induced voltages by integrating up to some higher harmonics. In Fig. 4, the compensating voltage is consists of the fundamental and the 2nd harmonic component.

As can be clearly seen from Fig. 4, the distortion of the accelerating voltage(thick solid line) is compensated.

Applying the accelerating voltage after compensation, the beam emittance in the phase space after 1000 turns are simulated and the results are shown in Fig. 5. Different from the Fig. 3, the beam shape is mostly not collapsed in all cases.

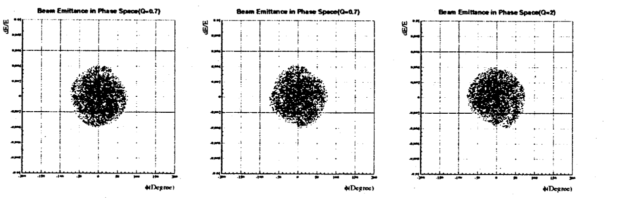

Figure 5: Beam emittance in a phase space after 1000 turns with beam loading compensation.

The particles are stably holded in the rf bucket even without the compensation, however more stable acceleration is achieved by the above mentioned harmonic compensation for the beam induced voltage.

3 The Measurement of Beam Loading

The beam loading measurement is under preparation. Electron beam generated by electron-gun is injected into the proto-type of MA loaded rf cavity. A schematic setup is shown in Fig. 6, and the parameters are shown in Table 2.

Electron Energy	~200 keV
Peak current	~7 A
Pulse width	50 ~ 80 nsec.

Table 2: The parameters of the electron-gun.

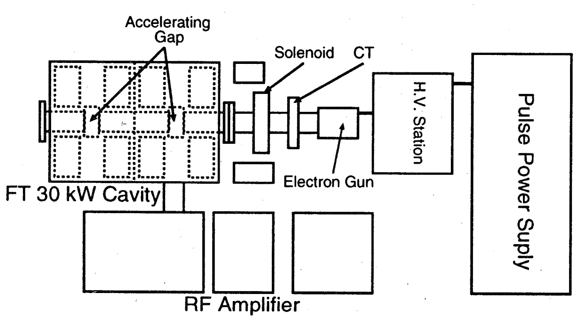

Figure 6: Schematic view of the beam loading measurement setup.

Using electron beams, the compensation scheme mentioned above will be tried.

4 Summary

The beam loading effects for the MA loaded rf cavity are investigated by the simulation. In order to suppress the beam loading effects, the compensation of the beam induced voltage up to 2nd higher harmonic on the rf frequency is fairly effective.

References

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