Longitudinal Emittance Control and Beam Loading Effects on Proton Synchrotrons in JAERI-KEK Joint Project

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Abstract

Longitudinal beam emittance should be controlled to alleviate space charge effects and to avoid beam instabilities by rf manipulations at proton synchrotrons in JAERI-KEK Joint High Intensity Proton Accelerator Project. Furthermore, heavy beam loadings should be compensated for stable acceleration. The cures for them are reported with particle tracking simulations.

1 INTRODUCTION

In the high intensity proton accelerator project at JAERI and KEK [1], there are two synchrotrons; one is 3 GeV Proton Synchrotron which is a rapid cycling one at a repetition rate of 25 Hz where 8.3 $\times 10^{13}$ protons are going to be accelerated from 400 MeV to 3 GeV within 20 ms. The other is 50 GeV Proton Synchrotron where 3.3 $\times 10^{14}$ protons are going to be accelerated from 3 GeV to 50 GeV at a repetition rate of 0.3 Hz. Main rf parameters and design works were summarized in the previous papers [2, 3, 4].

Since these machines are very high intensity ones, some cures should be considered at the rf system to suppress space charge effects, beam instabilities, bucket distortion and beam loading effects on the longitudinal beam motion.

2 EMITTANCE CONTROL

There are some requirements for the longitudinal beam property.

In 3 GeV PS, a bunching factor at injection and extraction should be large than 0.3 for alleviating the space charge effects [5], which is also important at the injection in 50 GeV PS since the bunches in 3 GeV PS are injected into 50 GeV PS by bucket to bucket transfer. Therefore, if the bunch with a bad bunching factor is injected into 50 GeV PS, it is estimated that the fast beam loss will occur within some hundreds μs.

In 50 GeV PS, the other cure should be considered for the microwave instability [5] because this machine has a long flat top for the slow extraction. In order to avoid such instability, it is proposed that longitudinal beam emittance is going to be blown up until the flat top.

2.1 Injection at 3 GeV PS

On the low energy region, since the space charge effects are dominant in the proton synchrotron, the peak beam current should be low as possible. Therefore, it is planned that 2nd higher harmonic voltage is added with the fundamental one to make the bunch shape flatten. In order to investigate the effect of the 2nd higher harmonics, particle tracking simulations on the longitudinal motion were performed.

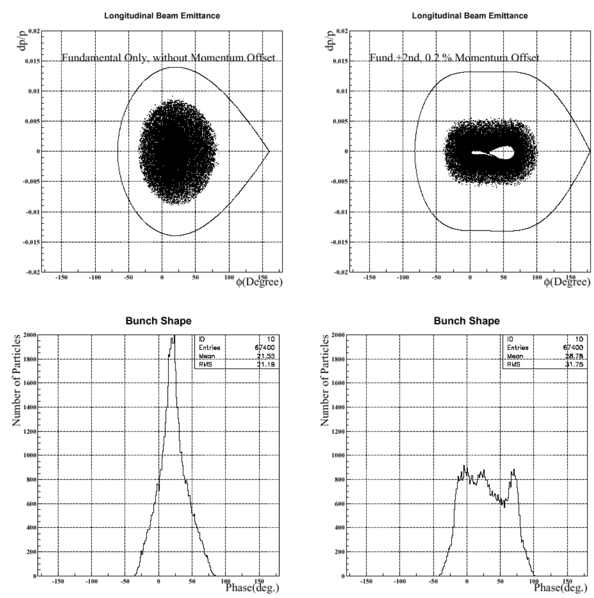

Figure 1: The beam emittance and the bunch shape at the injection in 3 GeV PS.

The Figure 1 shows the simulation result of the beam emittance on the longitudinal phase space and the bunch shape after 4 ms from the injection.

In this simulation, the multi-turn injection was simulated, that is, 400 MeV Linac provided macro bunches to 3 GeV PS during 337 turns. The macro bunch had a maximum of 1.235×10^{11} protons in 396 ns length and a momentum spread of $\Delta p/p \sim \pm 0.1\%$.

The left hand of Fig. 1 shows the result in the case of the fundamental accelerating voltage only. The particles were gathered to the center of the bunch, then the bunching factor became about 0.1. The right hand of the Fig. 1 shows the result in the case that 2nd higher harmonic was multiplied by the fundamental accelerating voltage. Furthermore, momentum offset of $\Delta p/p$ ~0.2 % with respect to the synchronous momentum was introduced to the injected bunches because the bunching factor was improved more. As clearly seen from the simulation results, the bunch shape was more flatten by these cures, then the bunching factor of 0.32 was achieved. This momentum offset is effective for not only improving the bunching factor but also blowing up the emittance at the extraction.

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2.2 Emittance Blow Up at 3 GeV PS

It is required at the slow extraction in 50 GeV PS that the beam emittance should be larger than 10.75 eVs [5], although the beam emittance becomes $\sim$ 3.2 eVs under the normal acceleration in 3 GeV PS. Therefore, there are three choices for the emittance blow up: it is completed at 3 GeV PS, it is completed at 50 GeV PS, or it is performed at both 3 GeV and 50 GeV PS. Firstly, we checked the first case by the particle tracking simulation including the space charge effect, although any kind of beam blow up scheme seems to be difficult in 3 GeV PS, because the synchrotron frequency is not so high near the extraction in 3 GeV PS such as one period per 1 ms as shown in Fig. 2.

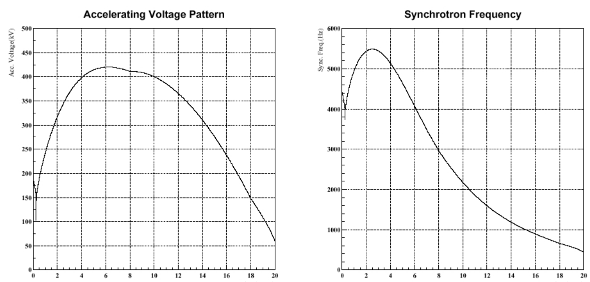

Figure 2: The accelerating voltage pattern and the synchrotron frequency at 3 GeV PS.

We tested a phase modulation of the rf voltage. The phase modulation was performed as follows;

$$\Delta E = eV \sin(\phi - \phi_m) \;, \quad (1)$$

$$\phi_m = \phi_{m0} \sin \omega_m t \;, \quad (2)$$

where ΔE, V, ϕ is an energy gain per turn of a particle, an accelerating voltage and a phase of each particle, respectively. ϕ_m is a phase which introduces the modulation with an amplitude ϕ_{m0} and a frequency ω_m. This modulation induces well-known parametric resonance, then we expect the beam emittance will be increased.

Firstly, we tried to multiply the 2nd higher harmonics. The left hand of Fig. 3 is the simulation result in the case of only fundamental rf voltage applying, and the right hand is the case of multiplying the 2nd higher harmonics during whole acceleration period. The multi-turn injection was demonstrated on both cases as described in previous section. As can be clearly seen, the beam emittance was almost same at both cases, but the bunching factor was fairly improved.

Next, we tried a phase offset injection and the phase modulation. The left hand of Fig. 4 are simulation results in the case of multiplying 2nd higher harmonics and introducing a phase offset of $\pi/6$ at the injection, and the right hand is the case of applying the phase modulation of $\phi_{m0} = 0.05$ radian and $\omega_m = 2\omega_s$, furthermore. The bunching factor was improved further on both cases than the case of simply multiplying the 2nd higher harmonics, and the bunching factor of about 0.26 was obtained. The beam emittance under the phase modulation became about 5 eVs and it was a little bit larger than that of about 4 eVs under no phase modulation. However, the beam emittance was dirty with the filamentation under the phase modulation and the beam core was hardly collapsed because there was not enough synchrotron oscillation period. Furthermore, the emittance occupied almost all of an acceptance rf bucket during acceleration, it seems that high intensity beam acceleration with the phase modulation has some risks.

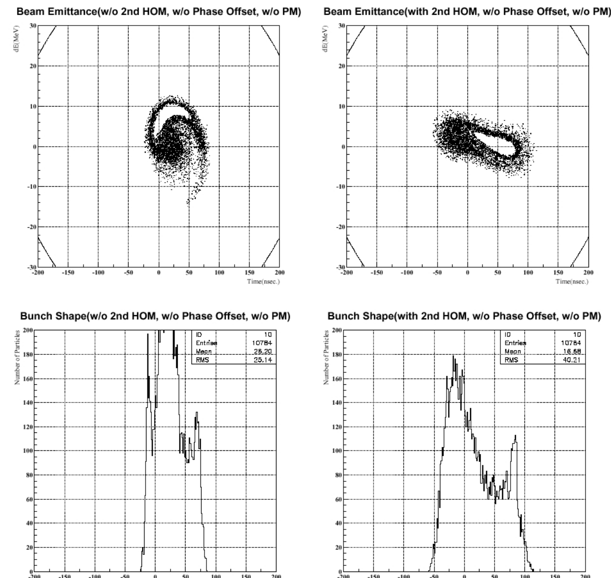

Figure 3: The beam emittance and the bunch shape at the extraction in 3 GeV PS from the view point of 2nd higher harmonics.

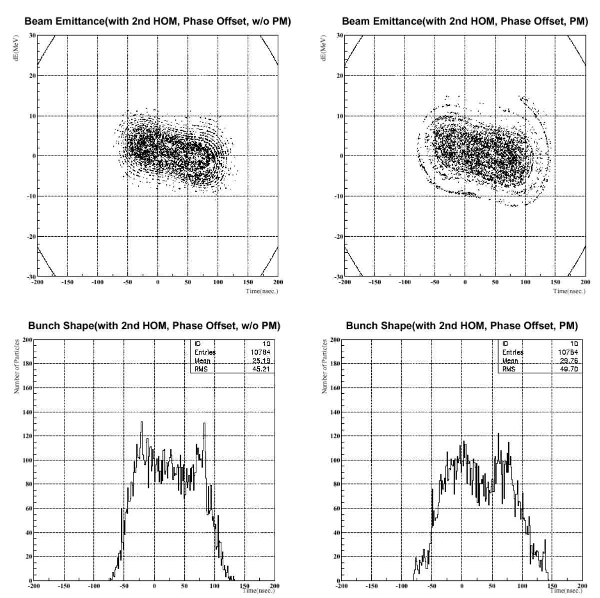

Figure 4: The beam emittance and the bunch shape at the extraction in 3 GeV PS from the view point of phase modulation.

2.3 Emittance Control at 50 GeV PS

This subject is now under investigation for the followings; the rf bucket matching between 3 GeV PS and 50

GeV PS to suppress quadrupole oscillation and maintain the bunching factor of 0.3, and the emittance blow up in 50 GeV PS until the extraction since enough emittance has not been obtained in 3 GeV PS.

3 BEAM LOADING

3.1 Feed Forward Compensation at 3 GeV PS

In 3 GeV PS, we plan to use the cavity with a quality factor of 2 in order to realize the acceleration without a resonant frequency tuning loop and add the 2nd higher harmonics with the fundamental one simultaneously in one cavity [2, 3]. Then, the wide-band impedance causes a wake field with some higher harmonics, it leads rf bucket distortion. Furthermore, the accelerating voltage at the injection and the extraction is going to be small in order to match the rf bucket size with the beam emittance, then it is estimated that the relative loading factor will be over 4 under the full intensity operation. In such case, a feed forward compensation for the beam loading is necessary to the stable acceleration, and we plan to adapt the compensation scheme by picking up the beam current and feeding into the cavity [6].

Then, we tried particle tracking simulation with the beam loading compensation, although the hardware to realize the beam loading feed forward compensation is now under investigation.

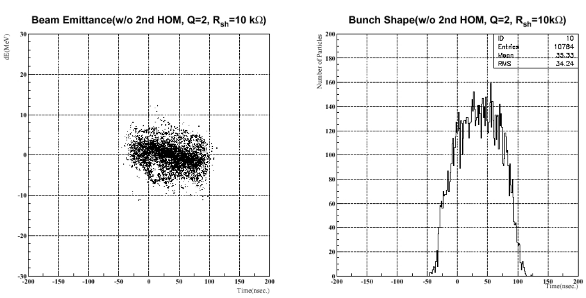

Figure 5: The beam emittance and the bunch shape at the extraction in 3 GeV PS including beam loading compensation.

The Figure 5 shows the simulation result with the beam loading and the space charge effects. The method of the simulation is described in [8]. In this simulation, the feed forward compensation up to the 2nd higher harmonics were done and multiplying the 2nd higher harmonics was turned off at 10 ms. From the result, the beam emittance was not so disturbed, so the feed forward compensation up to the 2nd higher harmonics was enough for the stable acceleration.

3.2 Feed Forward Compensation at 50 GeV PS

In 50 GeV PS, we plan to use the cavity with quality factor of 10, so the wake field caused by the cavity does not have so higher harmonic components. The relative loading factor becomes around 1 in 50 GeV PS, so it is not so severe than that in 3 GeV PS.

However, since the harmonic number is 10 and 8 bunches are filled in the rf bucket, that is, there are two empty bucket during acceleration, then the periodic transient condition occurs in 50 GeV PS. Furthermore, since there is the case of 4 or 6 bunch filling at the injection and the extraction, it makes the wake field with many side bands based on the revolution frequency, and it is more severe especially at the extraction because the bunching factor will become around 0.05. In such case, the feed forward compensation is going to be needed to suppress the rf bucket distortion. These subjects are now under investigation.

4 SUMMARY

The longitudinal emittance control was investigated mainly for 3 GeV PS. Using the momentum offset, the phase offset and the phase modulation, the bunching factor of 0.29 and the beam emittance of 5 eVs were obtained. However, the emittace almost occupied the whole rf bucket during acceleration, it must be improved more carefully.

The feed forward compensation of the beam loading was investigated mainly for 3 GeV PS. It was found that the compensation up to the 2nd higher harmonics was enough for the stable acceleration.

5 REFERENCES

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