SIMPSONS WITH WAKE FIELD EFFECTS

Y. Shobuda, F. Noda, JAEA, Tokai-mura, Naka-gun, Ibaraki-ken, Japan

S. Machida, CCLRC/RAL/ASTeC, Chilton, Didcot, Oxon, British
Y. H. Chin, K. Takata, T. Toyama KEK, Oho, Tsukuba-shi, Ibaraki-ken, Japan

Abstract

SIMPSONS, which is originally developed by S. Machida, is the program that calculates the space charge effect of the beam in the ring. We have installed the wake field effect into SIMPSONS, because the emittance growth not only due to space charge effects, but also due to the wake field effects is the important issue. The results of the simulation in J-PARC case are also represented.

INTRODUCTION

In Rapid Cycling Synchrotron (RCS) ring of J-PARC [1], there are many impedance sources. Especially, 8 extraction kickers that we will install are potentially one of the major sources of impedances in this ring. Recently, the measurements of the transverse impedance of this extraction kicker without the powering cables and the pulse-forming network etc. have been done [2]. It is necessary to investigate beam instability issues, which come from these extraction kickers.

It is important to develop the simulation code, which can deal with not only wake fields effect to the beam, but also space charge effects of the beam. G. Sabbi developed the moment method [3] to calculate wake field effects, while it is known that SIMPSONS [4], which was originally developed by S. Machida, is one of codes that calculate space charge effects of the beam in the proton synchrotron. It is possible to deal with both wake field effects and space charge effects simultaneously by modifying SIMPSONS.

In section 2, we review the moment method and explain how to install wake field effects into SIMPSONS. In section 3, we study wake field effects to the beam, which come from extraction kicker magnets from both the theoretical point of view and the simulation point of view. Summary is follows in section 4.

HOW TO CALCULATE WAKE EFFECTS

In this section we explain how to install wake field effects into SIMPSONS. In SIMPSONS, the independent variable is chosen as t-variable (time) in order to rigorously calculate space charge effects, while s-variable is suitable to calculate wake field effects because sources of impedances are located in each element of the ring. Due to this difficulty, we need some approximations to install wake field effects into SIMPSONS.

Before we explain these approximations, we review the moment method to calculate wake field effects. In the moment method, the distribution function of the beam is rewritten by the summation of the product of weight functions and the basis function. Once the wake potential for this basis function is calculated in advance, the wake potential for the general beam distribution function is calculated by the summation of the product of this wake potential and weight functions. In the case that the independent variable is chosen as s, weight functions and the longitudinal and transverse wake potentials are calculated simultaneously for the fixed s.

Since the independent variable is t in SIMPSONS, each particle is on the different position for fixed t. Therefore; we need some approximations in order to calculate wake potentials for fixed s. For this purpose, let us introduce the monitored point. When all particles of the beam pass through this point, we transform all positions of particles to the arrival time at the monitored position by assuming the drift transformation. Therefore, we obtain the distribution function of the beam: $\lambda(vt)$ at the monitored point.

The longitudinal wake potential $V_{\parallel}(vt)$ is calculated as

$$V_{\parallel}(vt) = \sum_{k=1}^{M-1} \lambda_k v_{\parallel}(vt - vt_k), \tag{1}$$

because the distribution function is rewritten by the summation of the basis function $f_k(vt)$ as,

$$\lambda(vt) = \sum_{k=1}^{M-1} \lambda_k f_k(vt), \tag{2}$$

where λ_k is the weight function, M is the number of bins and $v_{\parallel}$ is the longitudinal wake potential for the basis function. Following G.Sabbi, the basis function is chosen as the triangle function as follows,

$$f_k(vt) = \begin{cases} 1 - |vt - vt_k|/\Delta & vt \in [vt_{k-1}, vt_{k+1}], \\ 0 & vt \notin [vt_{k-1}, vt_{k+1}] \end{cases} \tag{3}$$

where Δ is the width of the bin.

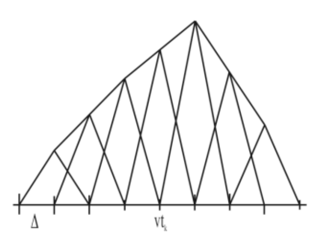


Figure 1: The longitudinal beam distribution, which is fitted by the triangle function.

For the transverse wake potential, the situation is more complicated. We need the transverse weight function d_k at the monitored point. For this purpose, we take a snap shot of the beam at first, when all particles of the beam pass through the monitored point. Then, we calculate

$$d_k' = \sum_{n=1}^{N} z^{(n)} \delta\lambda_k^{(n)}, f_k' = \sum_{n=1}^{N} z'^{(n)} \delta\lambda_k^{(n)}, \tag{4}$$

where

$$\delta\lambda_k^{(n)} = \begin{cases} (1 - |vt - vt_k|/\Delta) q/\Delta & vt \in [vt_{k-1}, vt_{k+1}], \\ 0 & vt \notin [vt_{k-1}, vt_{k+1}] \end{cases} \tag{5}$$

q is the charge of macro-particle, $z^{(n)}$ is the transverse coordinate, either x or y, and $z'^{(n)}$ is either x' or y' at this snap shot time. Then, we transform d'_k and f'_k to those at the monitored position by Twiss parameters, because each d'_k and f'_k is located at the different position at fixed t. This transformation is the important approximation to calculate the transverse wake potential. By this approximation, nonlinear information is partially lost. Since we obtain, d_k, we can calculate the transverse wake potential $V_\perp$ as follows,

$$V_\perp(vt) = \sum_{k=1}^{M-1} d_k v_\perp (vt - vt_k), \tag{6}$$

where $v_\perp$ is the transverse wake function for the basis function.

Since we obtain the longitudinal and transverse weight functions, we calculate the wake kick to the beam at the monitored position using Esq.(1) and (6) when each particle passes through the monitored position. After all particles are kicked, the snap shot is taken. Then, the weight functions are calculated for the next turn. The arrays for the weight functions and particle arrival time at the monitored position are prepared in order that the long range wake can be calculated. By iterating these processes, we can calculate effects of wake fields to the beam.

EFFECTS OF KICKER MAGNETS AT J-PARC

Using this simulation code, we discuss effects of 8 extraction kicker magnets at RCS of J-PARC. In RCS, chromaticity is not fully corrected at day one. There are two possibilities how to operate RCS. One possibility is that chromaticity is not corrected at all, another possibility is that chromaticity is corrected only at the injection energy by DC power supply on. Since kicker magnets are potentially one of the major sources of impedances, it is necessary to investigate beam instability issues on these operations.

Before we discuss this problem, we need to know the behavior of chromaticity for each operation in advance. Results are shown in Figure.2. When chromaticity is not corrected at all, it is –9. When chromaticity is corrected only at the injection energy, it becomes negative, as the energy of beam is bigger.

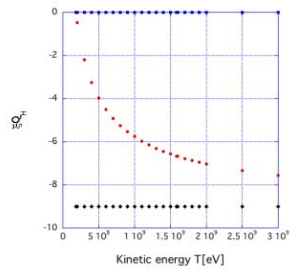


Figure 2: The behavior of chromaticity, ξQ_H for each operation. Red points represent the case that chromaticity is corrected by dc power supply on. Blue points do the case that it is fully corrected. Black points do the case that it is not corrected at all.

Recently, measurements of the transverse impedance of the extraction kicker without the powering cables and the pulse-forming network have been done by Toyama group. The wake function for this transverse impedance is written as follows,

$$W_T(z) = W_0 \left(\Theta(z) - \Theta\left(z - \frac{Lc}{v} \right) \right), \tag{7}$$

where W_0=3.5*$10^{10}\pi$[V/Cm], L=638[mm], v=0.0225c[m/s], $\Theta(z)$ is the step function. Here $W_T(z)$ is defined for the positive z. We should notice that there is no δ–function in Eq. (7). The interpretation of this reason and the relation between the impedance and wake function for the traveling wave kicker magnet was discussed in [2].

Theoretically, the growth rate can be calculated using the following formula [5].

$$\tau_m^{-1} = -\frac{1}{1+m} \frac{1}{4\pi Q_T} \frac{I_c c}{E/e} \sum_{p=-\infty}^{\infty} Z_T(\omega_p) F_m(\omega_p - \omega_\xi), \tag{8}$$

where

$$F_m(\omega) = \frac{h_m(\omega)}{B_f \sum_{q=-\infty}^{\infty} h_m(\omega_q - \omega_\xi)},$$

$$h_m(\omega) = \frac{\tau_L^2}{2\pi^4} (m+1)^2 \frac{1 + (-1)^m \cos(\omega \tau_L)}{\left\{ (\omega \tau_L / \pi)^2 - (m+1)^2 \right\}^2},$$

$$\omega_\xi = \frac{\xi \omega_\beta}{\eta}, \tau_L = \frac{B_f T_0}{h}, \omega_p = (ph + \mu)\omega_0 + \omega_\beta + m\omega_s,$$

m is the head tail mode number, μ is coupled bunch mode number, Q_T is tune, I_c is the average current, E is the energy of the beam, B_f is the bunching factor, ξQ_T is chromaticity and ω_β is the betatron frequency. Using parameters of RCS listed in Table 1, we obtain the dependence of the growth rate of transverse coordinates on chromaticity. The results are shown in Figure 3. Since repetition rate of RCS is 25MHz, both procedures that chromaticity is fully corrected and that chromaticity is not corrected at all are suitable from the beam instability point of view, while it looks like chromaticity crosses the large growth rate region during the acceleration, when chromaticity is corrected only at the injection energy.

The results of simulations are shown in figure 4. We confirm that the emittance growth is acceptable both cases that chromaticity is fully corrected, and that chromaticity is not corrected at all. Comparing the results between the case that chromaticity is fully corrected and that chromaticity is corrected only at the injection energy, we find that the emittance growth for both cases is almost the same around the injection energy, while it looks like the emittance growth is reduced thanks to the Landau damping even in the case that chromaticity is corrected only at the injection energy.

Table 1: Parameter list of RCS (harmonic number h=2)

T (Kinetic energy, GeV)	0.181(injection energy)	3(extraction energy)
f_0 (MHz)=1/ T_0	0.47	0.84
η(slippage factor)	-0.69	-0.047
Q_H/ Q_V	6.68/6.27	6.68/6.27
B_f (Bunching factor)	0.374	0.185
I_c (Average current, A)	3.74	6.7
ν_s	0.0058	0.0005

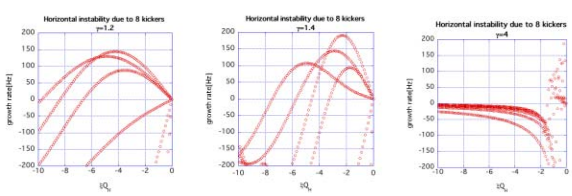
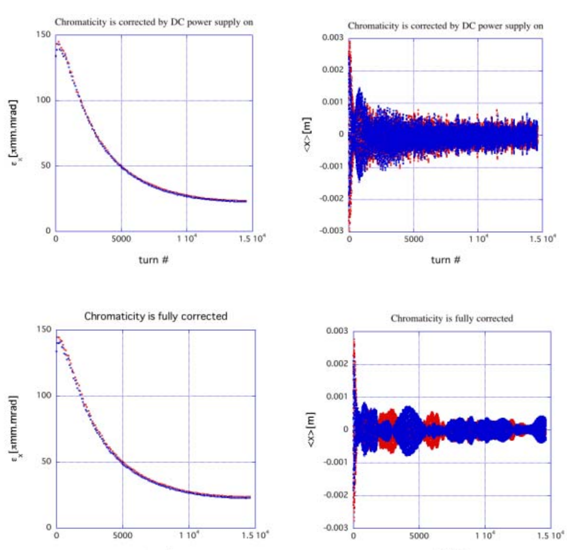


Figure 3: The growth rate due to 8 extraction kickers. The left figure shows the situation at the injection energy. The right figure does at the extraction energy (The growth rate is 0.00028Hz at ξQ_H=0.). The middle figure does at γ=1.4.



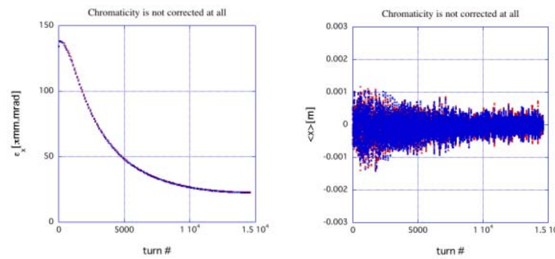


Figure 4: Emittances and averages of horizontal coordinate for the turn number (the beam energy). The upper figures represent cases that chromaticity is corrected by DC power supply on. The middle figures do cases that it is fully corrected. The lower figures do cases that it is not corrected at all. Blue points represent the case without impedance sources and red points do the case with kicker impedances.

SUMMARY AND DISCUSSIONS

We have installed wake field effects into SIMPSONS by applying the moment method. As an example of the utility of this code, we investigate the wake field effects come from kicker magnets to the beam at RCS in J-PARC. According to the simulation, the emittance growth is acceptable for both cases that chromaticity is not corrected at all and that chromaticity is corrected only at the injection energy by DC power supply on at day one.

Up to now, we simulate the case that the only wake field effects are included. Next, we have to study the emittance growth caused by both the wake field effect and space charge force.

Further, we will have to simulate the effect of kicker magnets with the powering cables and the pulse-forming network etc. It is planned that the measurements of the impedance of kicker magnets with the powering cables and the pulse-forming network etc. will be done in the near future.

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