DEVELOPMENT OF THE NEW MEASUREMENT METHOD FOR THE INCOHERENT TUNE SPREAD AND THE TUNE SHIFT CAUSED BY THE SPACE CHARGE EFFECT

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Abstract

For the high intensity hadron accelerator, the incoherent tune (ν_{incoh}) is shifted and decreases from the bare tune by the space charge force. In addition, the ν_{incoh} is formed into spread shape commonly. When the ν_{incoh} satisfies a resonance condition, it might occur that the beam emittance growth and the beam loss. So it is necessary to reduce the ν_{incoh} shift and the spread as much as possible. To achieve this condition, it is desired to measure the ν_{incoh} shift and the spread directly. Therefore, we are developing the new measurement method of the ν_{incoh} shift and the spread due to the space charge effect. From the simulation results, it became clear that the beam distribution could be modified in the case of using the mono frequency dipole exciter because a particle which had the tune corresponding to the exciter could be resonated temporary. In addition, it became clear that the measurement of the distribution transition could be means to evaluate the ν_{incoh} shift and the spread. We will report the concept of this method and the developing plan at the J-PARC 3GeV rapid cycling synchrotron (RCS).

INTRODUCTION

The proton synchrotron as a neutron or other secondary particles source is desired that the output beam becomes more high intensity in order to experiment more efficiently. For the hadron synchrotron, the beam intensity is restricted by the value of the beam loss because the beam loss causes the activation. When the activation is too high from a point of the exposure to radiation, we can't maintenance the accelerator. Therefore, the reduction of the beam loss is very important to achieve high intensity.

One of the sources of the beam loss is "incoherent tune spread". For the high intensity synchrotron, individual particles are received the repulsive force caused by the space charge effect. As a result, the incoherent tune (ν_{incoh}) which is the frequency of the individual particle is shifted and decrease from the bare tune because the force works as the defocus. In addition, the ν_{incoh} is formed into spread shape commonly because the repulsive force which individual particles are received is different particle by particle. This phenomenon is called the incoherent tune spread ($\Delta\nu_{incoh}$). If the ν_{incoh} satisfies a resonance condition by the $\Delta\nu_{incoh}$, it might occur that the beam emittance growth and the beam loss. So it is necessary to suppress the $\Delta\nu_{incoh}$ as much as possible.

To achieve this, it is desired to measure the $\Delta\nu_{incoh}$ directly. Therefore, we are developing the new measurement method of this applying RF knockout method.

APPLYING RF KNOCKOUT TO THE INCOHERENT TUNE MEASUREMENT

One of the methods for the tune measurement at a synchrotron is the RF knockout method. When the dipole exciter is applied and excites mono frequency, the beam which has the tune corresponding to the exciter frequency resonates and the beam loss occurs. Therefore, we can determine the tune by seeking the exciter frequency. However, this tune is "coherent tune" determined by movement of the whole beam.

When the dipole kick source is applied and it is assumed that the space charge force is linear, the beam oscillation equation is given as follows:

$$\frac{d^2x}{ds^2} + k_{ex}x = F\cos(\omega) + k_{sc}(x - \bar{x}), \qquad (1)$$

where k_{ex} is the external focusing force, k_{sc} is the space charge force, $F\cos(\omega)$ is the dipole RF kick and $\bar{x}$ is average value of x [1][2]. By averaging, Eq. (1) is modified as

$$\frac{d^2\bar{x}}{ds^2} + k_{ex}\bar{x} = F\cos(\omega). \qquad (2)$$

Subtract Eq. (2) from Eq. (1), we can get

$$\frac{d^2(x - \bar{x})}{ds^2} + (k_{ex} - k_{sc})(x - \bar{x}) = 0. \qquad (3)$$

According to Eq. (2) and (3), the dipole kick affects only coherent motion. In other word, the ν_{incoh} doesn't react to the dipole kick fundamentally because the motion of individual particles from $\bar{x}$ isn't affected by the dipole kick as the Eq. (3) suggests.

However, it is also considered that individual particles resonate when the ν_{incoh} and the exciter frequency are same. Therefore, it was examined that how the dipole RF kick affects individual particles by the multi-particle simulation.

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REACTION OF THE INCOHERENT TUNE TO THE DIPOLE KICK

The Incoherent Tune Spread at the J-PARC RCS

The reaction of the ν_{incoh} to the mono frequency dipole exciter was researched by the multi-particle simulation. In this examination, the 3 GeV rapid cycling synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) is supposed [3]. The RCS is a high intensity proton accelerator and serves as a neutron or other secondary particles source. Beams from a linac with a kinetic energy of 181 MeV are injected turn by turn dividing 235 in order to achieve high intensity. During the injection, injection beams are shifting slightly from the central orbit in order to spread the beam size intentionally and suppress the charge density [4]. The simulation results of the tune diagram and the $\Delta\nu_{incoh}$ after injection are shown in Fig. 1.

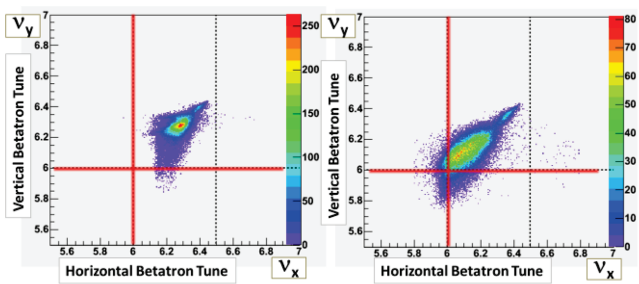

Figure 1: The tune diagrams and the $\Delta\nu_{incoh}$ after injection. The left and right figures are the case of 100 kW and 200 kW beam power respectively. The bare tune is (6.43, 6.43).

It is considered that particles whose ν_{incoh} becomes close to an integer mainly cause the emittance growth and the beam halo at the RCS. Therefore, the measurement of the $\Delta\nu_{incoh}$ is desired.

The Emittance Growth caused by Dipole Exciter

In the simulation, the mono frequency dipole exciter was added at a part of the RCS ring. The 100 μrad. vertical RF kick was applied after injection. The RF frequency was determined to be same with ν_{incoh}. In this simulation, the beams are not accelerated, though those are captured by the fixed RF bucket. The circling period is 2.13 μsec. The simulation results are shown in Fig. 2. The vertical axis is the vertical ν_{incoh} and horizontal axis is the vertical emittance. Each particle's points in the phase space are converted into emittance using α and β function of the ring.

From these results, it became clear that the ν_{incoh} became higher than the exciter frequency by the dipole exciter when the exciter frequency was satisfied any one of the $\Delta\nu_{incoh}$. This phenomenon can be explained as follow. First, the particle whose ν_{incoh} is same with the exciter frequency resonates temporally and its emittance increases. Next, the ν_{incoh} of particles whose emittance is smaller than resonated particle's one increases because the space charge force is mitigated. Then, the particle whose ν_{incoh} becomes same with the exciter frequency resonates temporally again. This process is repeated.

In addition, it became clear that the distribution of ν_{incoh} was not affected by the exciter when the exciter frequency was not satisfied any one of $\Delta\nu_{incoh}$.

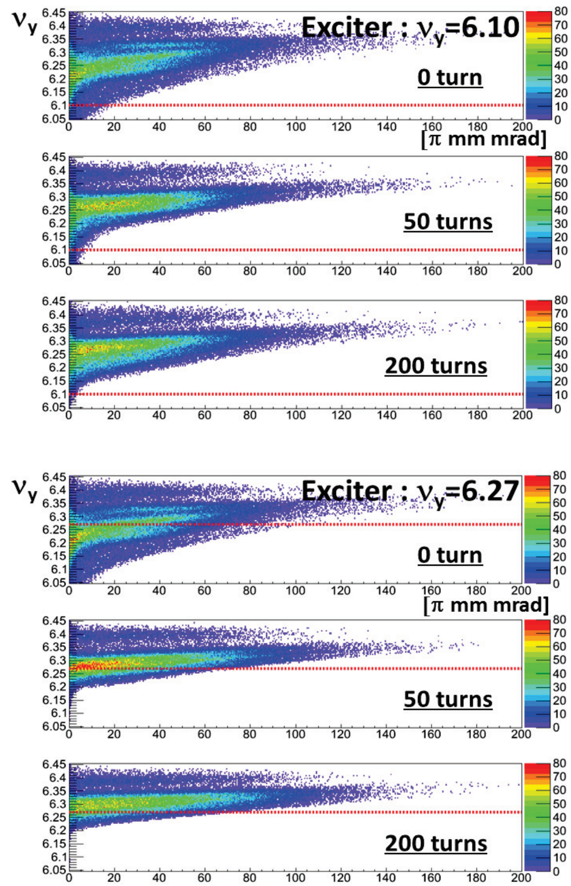

Figure 2: The particle plots of the vertical ν_{incoh} vs emittance applying mono frequency exciter kick at 100 kW beam power. Two frequency patterns are shown and each pattern includes three circling turn results. The red dot lines indicate the exciter frequency.

STUDY OF THE INCOHERENT TUNE MEASUREMENT

The Observation Method of the Emittance Growth

The observation method of the reaction of the ν_{incoh} to the dipole kick should be examined. In the RCS, the real space distribution of the beam can be measured. Especially, the Ionization Profile Monitor (IPM) [5] is powerful instrument for that purpose. When the

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circulating beam passes through the residual gas in the beam duct, the positively charged ions and electrons are produced. The IPM leads these ions or electrons to the transverse direction by the external electric field. By detecting these particles, the horizontal or vertical beam profile is obtained. Because the IPM is the non-destructive monitor, beam profiles can be obtained turn by turn continuously. For this reason, the modification of the beam profile caused by mono frequency dipole exciter was examined by the simulation.

The Beam Profile Modification by Dipole Exciter

In the RCS, some distributions can be formed if the shifting pattern of injection beam is controlled. Particularly, two pattern injection modes are adopted in the RCS [4]. One is the "Correlate" mode. The injection beam is moved away from the central orbit both horizontal and vertical in the phase space. The other is the "Anti-Correlate" mode. The injection beam is moved away in the horizontal phase space and closed to the central orbit in the vertical phase space. The Anti-Correlate mode can more suppress $\Delta\nu_{incoh}$ than the Correlate mode theoretically. The simulation results of the vertical $\Delta\nu_{incoh}$ are shown in Fig. 3. In this figure, the normal Anti-Correlate mode result (Anti-Correlate) and the modified Anti-Correlate mode result (Anti-Correlate-2) which is adjusted the beam shifting speed are shown.

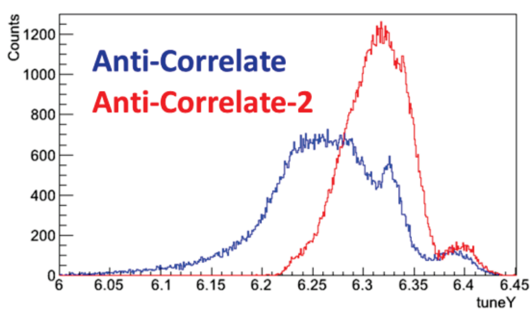

Figure 3: Two vertical $\Delta\nu_{incoh}$ distributions. The blue line is normal Anti-Correlate mode result. The red line is modified Anti-Correlate mode result. The bare tune is (6.43, 6.43).

In this way, some different distributions and $\Delta\nu_{incoh}$ can be formed by the injection process in the RCS. The beam profile modifications of these two distributions by the dipole kick exciter were simulated. The 100 μrad. vertical RF kick was applied and the vertical distribution was obtained. The results after 200 turns are shown in Fig. 4.

The black lines indicate the distribution without the exciter. From this result, it became clear that the beam profile modification occurred to reflect the emittance growth by the dipole kick. The distributions are different depending on the exciter frequency. In addition, these modifications are different from each other $\Delta\nu_{incoh}$ distribution. For example, the peaks were reduced and the distributions were spread for Anti-Correlate by ν_{incoh} = 6.22 and 6.27 exciter frequency but these were not very different for Anti-Correlate-2. These results suggest that the $\Delta\nu_{incoh}$ size and shape can be detected using an IPM and a dipole exciter.

On the other hand, when the kick angle was 10 μrad., the distribution was hardly changed compared with one without the exciter. This result suggests that a sufficient large kick angle is required in order to lead to the emittance growth.

Future Plan

It is desired by the further simulations and the analysis that the establishment of the $\Delta\nu_{incoh}$ measurement method using the dipole kick and the beam profile modification. In addition, it is required that the estimation of the dipole RF exciter which can apply sufficient kick angle.

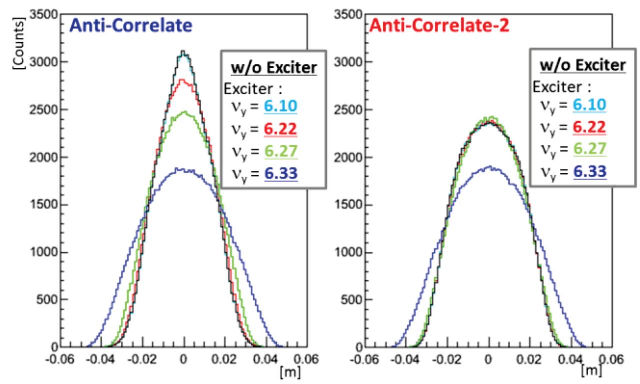

Figure 4: The vertical distributions with or without dipole exciter after 200 turns. The left figure is normal Anti-Correlate mode result. The right line is modified Anti-Correlate mode result.

SUMMARY

It became clear that the ν_{incoh} resonated temporary and the emittance growth occurred when the dipole exciter frequency was satisfied any one of $\Delta\nu_{incoh}$ by the multi particle simulation. In that case, it also became clear that the ν_{incoh} became higher than the exciter frequency. Now, the detection method of the $\Delta\nu_{incoh}$ size and form is under investigation by observing that resonance phenomena as the beam profile modification.

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