COHERENT SYNCHRO-BETA COUPLING IN THE KEK DIGITAL ACCELERATOR

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Abstract

The KEK Digital Accelerator is a small-scale fast cycling induction synchrotron, where induction pulse voltages discretely accelerate heavy ion beam. Its voltage height V_{out} is constant due to a technical restriction and does not correspond to the required acceleration voltage per turn $V_n=\rho C_0[dB/dt]$ at the n-th turn. The induction acceleration system is triggered when $\Sigma\ V_n\ -\delta\Sigma\ V_{out}. > V_{out}$ (δ=1 when acceleration voltage is supplied. δ=0 when acceleration voltage is not supplied). Consequently, a perturbation on the betatron oscillation induced by a discrete change of the equilibrium orbit becomes notably large. A size of this perturbation is quantitatively estimated by means of numerical simulation and is compared with the experimental result.

INTRODUCTION

The KEK Digital Accelerator (DA) [1,2] is a small-scale fast-cycling induction synchrotron that does not require a high-energy injector (see Fig. 1). The induction acceleration system shown in Fig. 2 was developed to demonstrate the induction synchrotron concept in 2006 using the KEK 12-GeV proton synchrotron [3], which is a typical slow-cycling synchrotron. There are two basic technical issues for induction acceleration in the KEK-DA.

1. An induction cell is employed as the acceleration device, which is simply a one-to-one pulse transformer energized by a switching power supply (SPS) generating pulse voltage pulses. The SPS is connected to the DC voltage power supply. The output voltage height for acceleration, V_{acc}, is necessarily determined by the setting voltage of the DC power supply, which is fixed to a constant value in the range from 0.3 kV to 2.0 kV per cell within the acceleration cycle.
2. The KEK-DA ring does not have dispersion-free regions. The induction acceleration cells are placed at the region where the size of the momentum dispersion function is 1.4 m.

Since the guiding magnetic fields of the KEK-DA are excited sinusoidally, an ideal profile of V_{acc} is of half sine shape as shown in Fig. 3. The ideal profile of V_{acc} is not realized because of the technical reason 1.

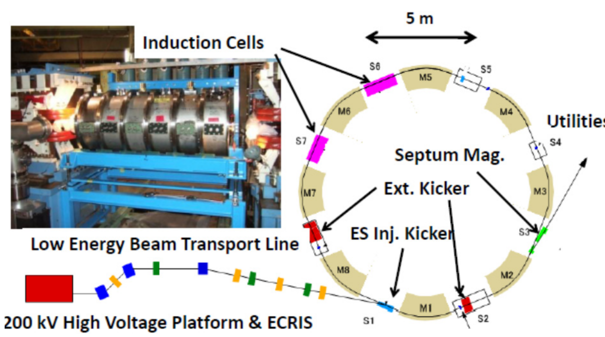

Figure 1: Schematic view of the KEK-DA.

In the early and late stages of acceleration, the required acceleration voltage is lower than the fixed output voltage of the induction cell. Thus, the pulse density of the acceleration voltage must be controlled. This is actually carried out in the following way. Gate trigger of the solid-state switching elements employed in the SPS is generated when the integrated required acceleration voltage V_{req} reaches V_{acc} of the induction cell, resulting in the production of V_{acc} at the induction cell. This method has been called "pulse density control" since its proposal [4].

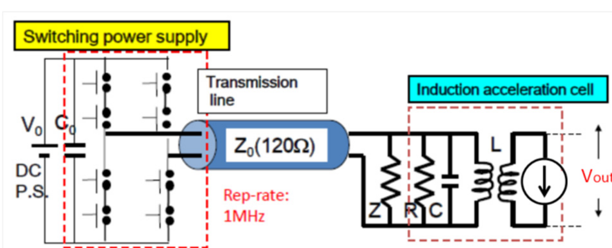

Figure 2: Equivalent circuit for the induction acceleration system, where the induction cell with a matching resistor is connected to the SPS through a 120 Ω transmission line.

The individual equilibrium orbit $D(s)\Delta p/p$ of particles changes gradually associated with ramping of the guiding magnet until the acceleration voltage is generated. The equilibrium orbit of an assumed particle located at the bunch center should return to position zero after acceleration voltage generation. The oscillation amplitude and phase of the betatron motion of an individual particle, however, simultaneously change, because the actual orbit $x(s)=x_\beta(s)+D(s)\Delta p/p$, which is a deviation from the ideal orbit, never changes at the acceleration gap position. If momentum dispersion function vector ($D(s)$, $D'(s)$) at the

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acceleration gap position, where $\Delta p/p$ changes discretely with acceleration voltage generation, is zero, the oscillation amplitude and phase of the betatron motion never change. The beam is completely free from crucial issues discussed here. The present KEK-DA is not the case because of the technical reason 2.

TYPICAL INDUCTION ACCELERRATION UNDER VOLTAGE PULSE DENSITY CONTROL

An typical example of induction acceleration under the pulse density control is shown in this section, where the following machine parameters of the KEK-DA are assumed,

Table1: Machine Parameters of the KEK-DA

Circumference of the beam orbit	C_0=37.7 m
Bending raius	ρ=3.3 m
Repetition rate	f=10 Hz
Maximum bending flux density	B_{max}=0.84 T.

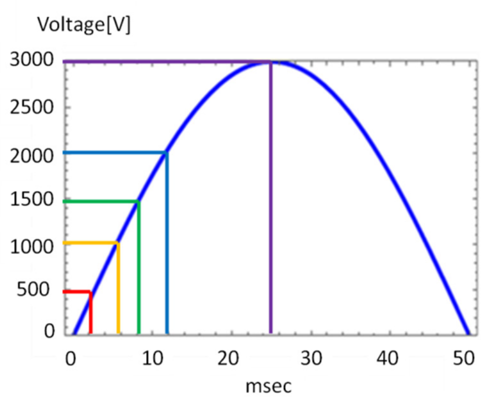

Figure 3: Required acceleration voltage per turn.

The required acceleration voltage V_{req} is shown in Fig. 3, Fig. 4 shows the timing to generate actually V_{acc} at the area to generate V_{acc}=0.5 kV, which the area which 500 V from zero in Fig. 3.

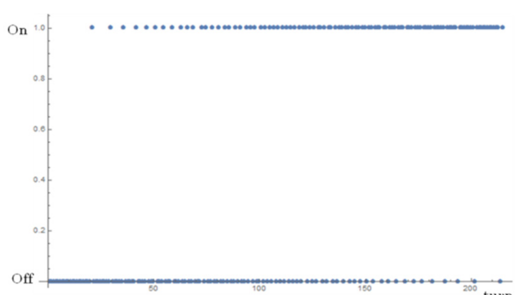

Figure 4: Timing to generate the induction voltage pulse.

5 of V_{acc}, which is 0.5 kV, 1.0 kV, 1.5 kV, 2.0 kV and 3.0 kV, is generated in this acceleration simulation (see Fig. 5). Barrier voltage V_{bb} is always 1.0 kV.

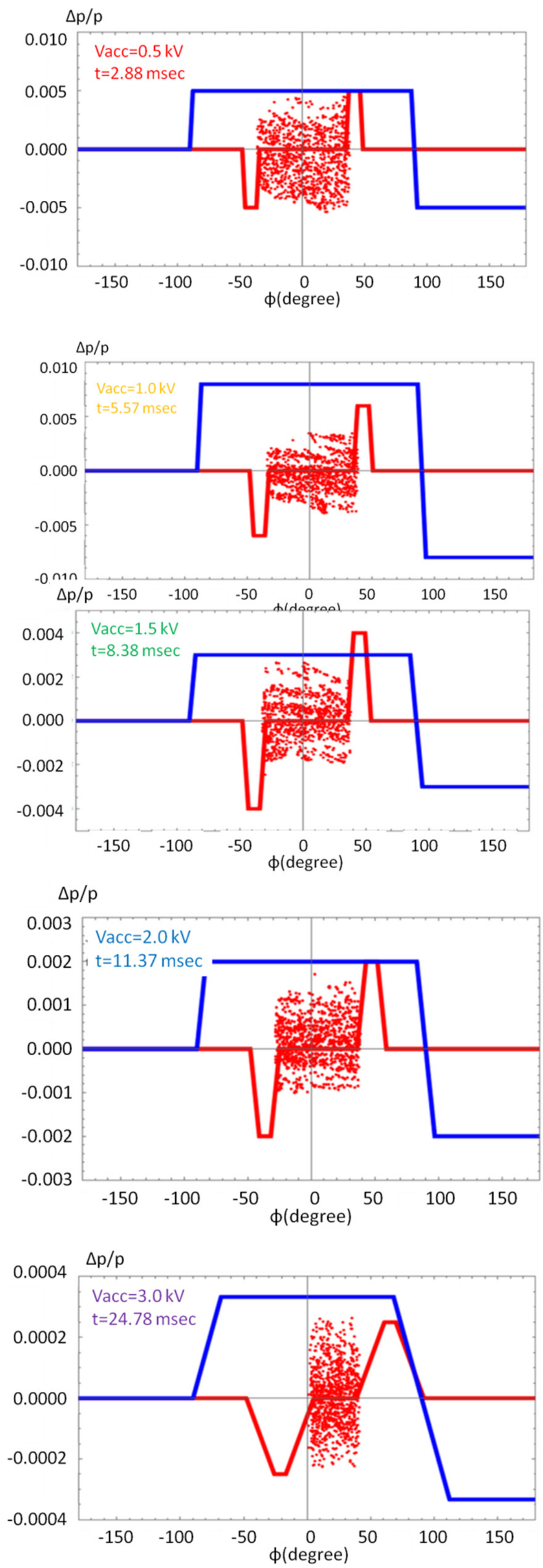

Figure 5: Discrete acceleration (Red and blue lines V_{bb} and V_{acc}, respectively).

BETATRON MOTION AND DISCRETE CHANGE IN THE EQUILIBRIUM ORBIT

The Poincare plane to observe the betatron motion at the acceleration cell position is shown together with tracks of two particles sharing the same equilibrium orbit denoted by O before getting the acceleration voltage in Fig. 6. In the other word, the two particles have the same momentum deviation $\Delta p/p$. The origin O' indicates the position of the ideal particle. For simplicity it is assumed that two particles have the same betatron amplitude but betatron phase different by π. The equilibrium orbit $D(s)\Delta p/p$ moves gradually from O' to O since the previous acceleration, because the acceleration voltage pulse is not triggered until the next trigger timing in the pulse density control scenario. The averaged orbit of the two particles places at O during the time interval between the previous acceleration and the next acceleration. The equilibrium orbit returns to O' just after the next acceleration. At this moment, the amplitude and phase of the betatron motion of the two particles vary as shown in Fig. 6. This is caused by a fact that the actual orbit $x(s)=x_\beta(s)+D(s)\Delta p/p$ does not change. As a result, the averaged orbit of the two particles never stay at the same position but should oscillate with a gradual drift toward the left side. We can say that some coherent betatron oscillation is induced.

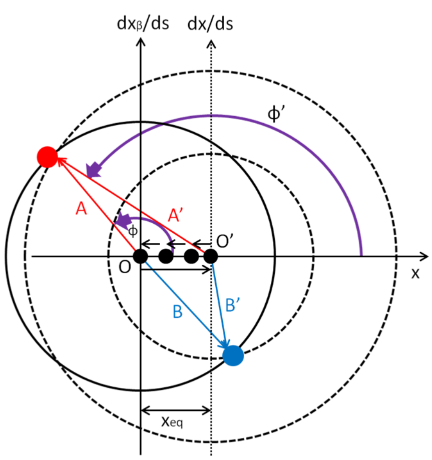

Figure 6: Betatron motions in the phase space.

In order to understand more realistic behaviors of the bunch of particles, macro-particle simulations have been extensively carried out, where 5000 macro-particles uniformly distributed in the horizontal phase space at beginning are assumed and the position of the bunch centroid is evaluated every turn. The beam centroid is shown as a function of turn number in Fig. 7. Two different acceleration voltage Plan A and B have been considered. In Plan A the voltage profile is divided into three stages, in which V_{acc}=0.2 kV (1~300 turns), 0.7 kV (301~800 turns), and 1.2 kV (801~1000 turns). In Plan B V_{acc} is always 1.2 kV (1~1000 turns). It is clear that in both cases of Plan A and B the oscillation amplitudes of the beam centroid increase with turn coherently. Even so, it is observed that its increasing is suppressed in Plan A employing the small step-size change in the acceleration voltage.

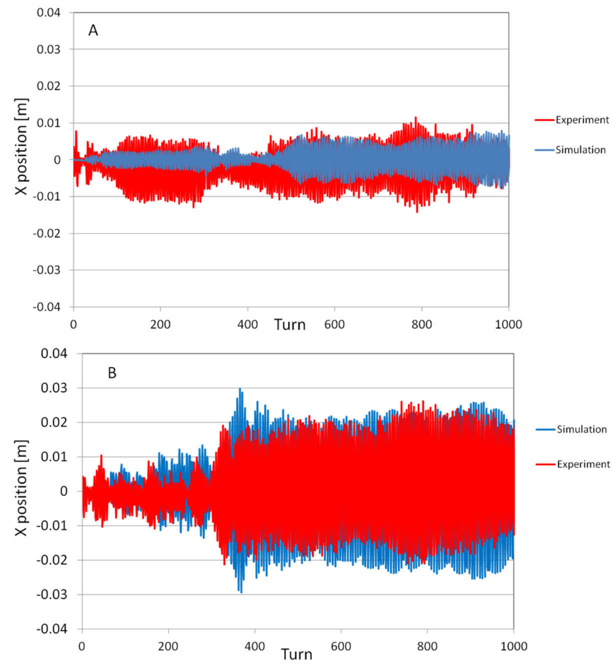

Figure 7: Simulation (blue) and experimental (red) results of temporal evolution of the beam centroid for Plan A and Plan B.

COMPARISON WITH EXPERIMENTAL RESULTS

In the experiments, the beam centroid was observed at the location of $D(s)=1.4$ *m* and $D'(s)=0$ by the position monitor, which is located at S4 in Fig. 1. The experimental results are shown in red lines [2]. It may be conculded that the simulation result reproduces the experimental result at a sufficient level.

CONCLUSION

It has been confirmed from both of the experiment and simulation that the discrete acceleration under the pulse density control scenario induces the coherent oscillation of the beam centroid. It has become clear that this coherent oscillation is suppressed by changing the acceleration voltage in a small step. The present result suggests what must be taken in a future ideal induction synchrotrons [5].

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