SUPER-BUNCH INDUCTION ACCELERATION SCHEME IN THE KEK DIGITAL ACCELERATOR

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Abstract

KEK Digital Accelerator (KEK-DA) [1] is a fast cycling induction synchrotron with induction cells driven by switching power supplies (SPS). The rectangular pulse voltages are precisely controlled by a field-programmable gate array (FPGA). One of our next missions for the KEK-DA is to demonstrate super-bunch (very long beam) acceleration technique in which the beam occupies over half of the ring at injection [2]. For that, power supplies for the SPS have to be upgraded from fixed voltage to time-varying voltage to provide beam-required acceleration. This is effective to suppress the blow-up of the longitudinal emittance and ensures the super-bunch acceleration stably.

INTRODUCTION

The concept of induction synchrotron was originally invented by Takayama and Kishiro in 2000 [2] and then a super-bunch hadron collider was proposed in 2002 [3]. The proof-of-principle experiment for induction synchrotron was successfully performed in the KEK 12GeV PS synchrotron in 2007 [4]. After that, the same group developed the KEK-DA, a small prototype of fast cycling induction synchrotron, which was converted from the old PS 500MeV booster ring. With this machine, the wide-band acceleration as a novel scheme of induction synchrotron was demonstrated [5], in which the revolution frequency can be increased by a factor of more than 10 in one acceleration cycle.

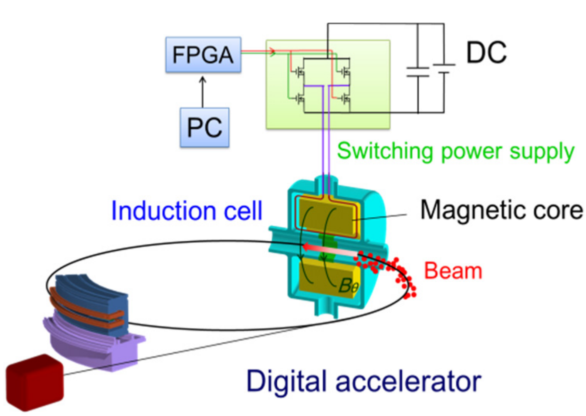

Figure 1: The Overview of the KEK-DA.

The schematic view of the KEK-DA is shown in Fig. 1. Heavy ion beams are produced in the electron cyclotron resonance ion source (ECRIS) and accelerated by the extraction voltage of 200 kV. Then, they are directly injected into the ring by the electrostatic injection kicker. The timings of the acceleration pulses are precisely controlled by a FPGA. The optimization of the timing is made following the ramping magnetic flux density of the bending magnets $B(t)$ [6].

In the current setup of the KEK-DA, fixed DC power supplies provide acceleration voltages for induction cells as shown in Fig. 1. It is difficult to give the acceleration voltages precisely following the required acceleration voltage per turn $V(t)$ ($= \rho C_0 dB(t)/dt$) that is necessary for the curvature radius of the ion in the bending magnet ρ and the circumference of the beam orbit C_0. In order to avoid the discrepancy, the acceleration voltage has to be generated intermittently as they correspond with the required acceleration voltage equivalently. The detailed discussion was already reported in other places [5, 7]. Although the present scheme can achieve the wide-band acceleration, it generates some synchro-beta coupling in horizontal direction and longitudinal emittance blow-up at the initial acceleration stage. In such a way to reduce both effects, an upgrade plan with time-varying DC power supply is considered in the next section. Furthermore, this plan can be adapted to super-bunch acceleration scheme.

ACCELERATION SCHEME

In induction acceleration, confinement and acceleration voltage can be generated independently as shown in Fig. 2. Two sets of confinement voltages produce a beam bucket with the length of one third of a beam revolution period at every turn. The height and width of the positive pulse are the same as the negative pulse. On the other hand, the required acceleration voltage changes continuously in the whole acceleration period. The positive pulse height is the half of the negative one, whereas the positive width is twice of the negative one to prevent magnetic cores of induction cells from saturation. This means that the acceleration pulse is asymmetric different from other existing accelerators.

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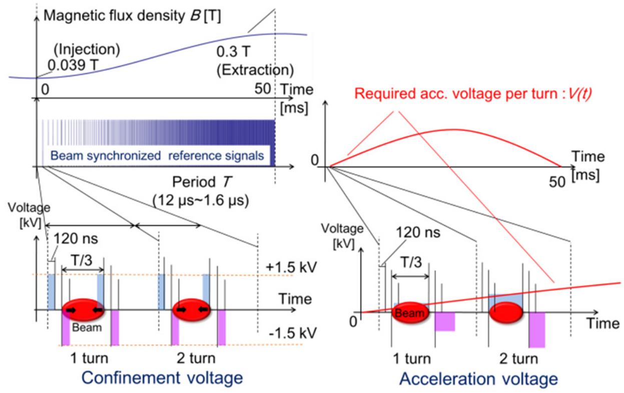

Figure 2: The proposed acceleration scheme for super-bunch acceleration at the KEK-DA.

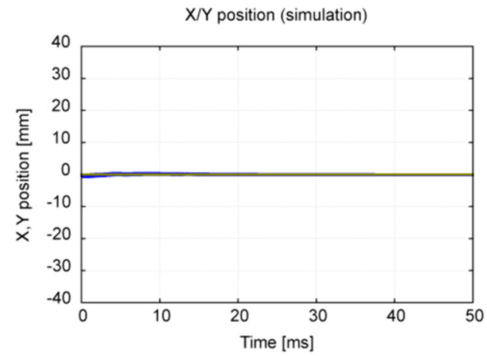

Figure 4: Horizontal (blue) and vertical (yellow) beam position in super-bunch acceleration at the KEK-DA.

PARTICLE TRACKING

In this simulation, a heavy ion beam with injection energy of 200 keV and mass to charge ratio of 4 is accelerated under the condition that the ramping magnetic flux density of the ring increases from 0.039 T to 0.3 T in 50 ms. The beam revolution frequency also increases from 82 kHz to 628 kHz correspondingly. The number of macro particle is 5000 with the momentum spread of 0.17 % as one sigma of Gaussian distribution and the length of 4 μs at the injection. The height of the confinement voltage is 1.5 kV with the rising and falling time of 80 ns. The longitudinal beam motions at the initial stage were shown in Fig. 3.The detail parameter set of this simulation is written in Ref. [7].

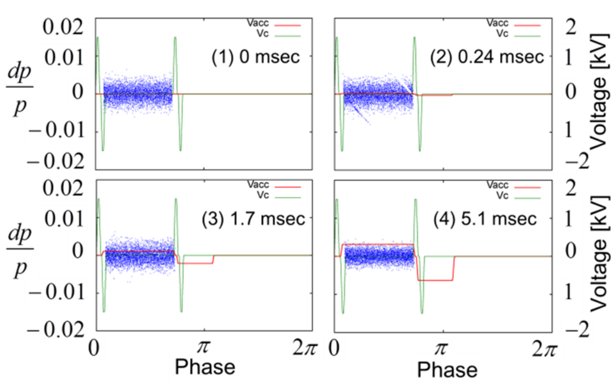

Figure 3: The longitudinal beam motion in the initial acceleration stage under the time-varying induction acceleration (simulation).

The longitudinal emittance decreases by the adiabatic dumping in Fig. 3. Ideal confinement and acceleration waveforms are shown in green and red line, respectively.

The horizontal oscillation caused by the synch-beta coupling is negligible small as shown in Fig. 4 because the acceleration voltage gradually changes in one acceleration cycle.

From the data set, the mountain plot is generated in the 3D space where the horizontal axis, vertical axis, and third axis denote the revolution time per turn, the time from injection, and the beam intensity, respectively. Its projection on the x–y plane is shown in Fig. 5 (a). The beam is confined uniformly in the whole acceleration. With the same axes, Fig.5 (b) and (c) are the time-turn plane view of confinement waveform with the height of ± 1.5 kV and acceleration waveform, respectively. The positive acceleration height is the half of the negative one and gradually changes as it follows the required acceleration voltage. The time width of positive pulse is twice of the negative one at every turn.

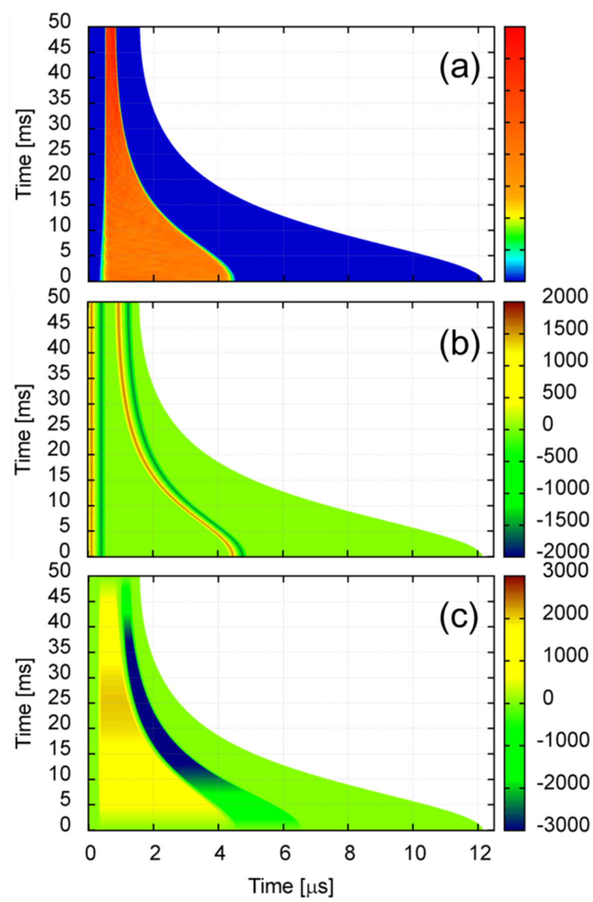

Figure 5: (a) Longitudinal beam motion in the initial acceleration stage under the time-varying induction acceleration (simulation), (b) Time-turn plane view of confinement voltage where positive set pulse and negative

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reset pulse are in red and blue (simulation), (c) Time-turn plane view of acceleration voltage where set pulse and reset pulse are in yellow and blue (simulation).

HARDWARE SYSTEM

To realize above acceleration voltage with the existing equipment of the KEK-DA, the smart acceleration system is contrived as shown in Fig. 6. The two DC-DC converters are connected to the switching power supply to provide time-variable asymmetric acceleration waveform which has positive and negative acceleration pulses with different heights.

Figure 7 shows the LT-spice model of the circuit in Fig. 6. The height of positive acceleration voltage corresponds to the required sinusoidal acceleration voltage throughout the entire acceleration cycle. The power supply voltage to the SPS follows the reference sinusoidal waveform through the single feedback system. In addition, a voltage drop circuit is embedded so that the height of the acceleration voltage can follow the required one smoothly.

The negative acceleration pulse has the same system.

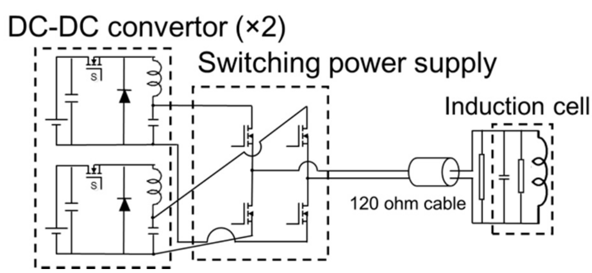

Figure 6: Induction acceleration system with two DC-DC convertors in order to generate asymmetric and time-variable acceleration pulse.

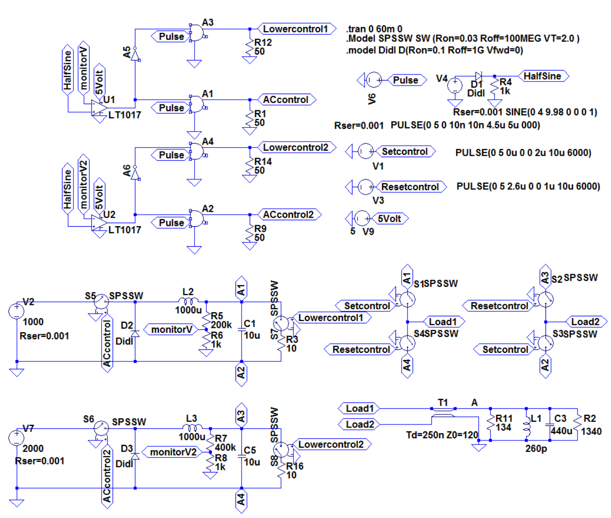

Figure 7: LT-spice model in order to generate asymmetric and time-variable acceleration pulse.

The acceleration waveform at the induction cell in one acceleration cycle is shown in Fig. 8 (a). The positive envelope is a sinusoidal waveform corresponding to the required acceleration voltage and the half of the negative envelope. The expansion view around 10 ms from the injection time is shown in Fig. 8 (b). The non-uniform spikes of the waveforms of Fig. 8 (a) and (b) originate from the calculation accuracy.

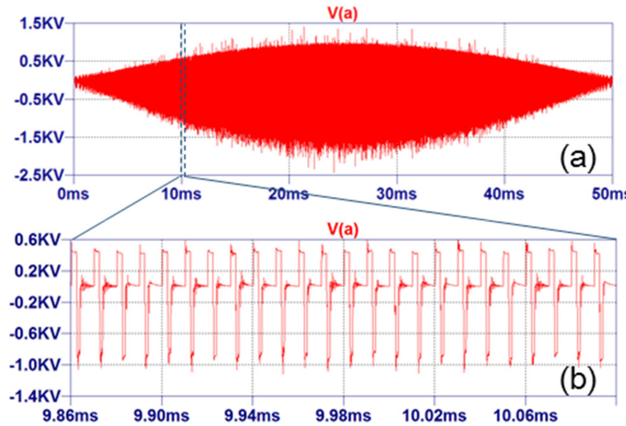

Figure 8: (a) Acceleration waveform with the proposed induction acceleration system. (b) Expansion view around the 10 msec from the injection time.

This calculation with LT-spice shows that it is possible to develop an induction acceleration system which generates asymmetric and time-variable acceleration pulse in principle.

CONCLUSION

The super-bunch acceleration scheme of induction synchrotron and its hardware system are discussed with simulation. These results suggest that super-bunch acceleration is feasible on condition that its beam loading effect is ignored.

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