WIDE-BAND INDUCTION ACCELERATION IN THE KEK DIGITAL ACCELERATOR*

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Abstract

Induction synchrotron is a new type of synchrotron using induction acceleration, not RF acceleration. This can achieve three possibilities: super bunch (very long beam) acceleration, wide-band acceleration and beam handling. Recently, we have established the wide-band acceleration technique at KEK digital accelerator which is a small scale prototype of fast cycling induction synchrotron [1]. It can accelerate any ion species directly to higher energy without a large pre-accelerator, due to its intrinsic nature that there is no frequency band-width limitation below 1 MHz. It has been confirmed that heavy ion beams of mass to charge ratio $A/Q = 4$ are stably accelerated from 200 keV to a few tens of MeV, where the revolution frequency changes from 82 kHz to 1 MHz in this accelerator ring. In this paper, the wide-band induction acceleration is presented with experimental results.

INTRODUCTION

Induction synchrotron has three possibilities: super bunch (very long beam) acceleration [2], wide-band acceleration (all ion acceleration) [3], and novel beam handlings. These functions can be achieved by high-speed semiconductor switching described in the next section.
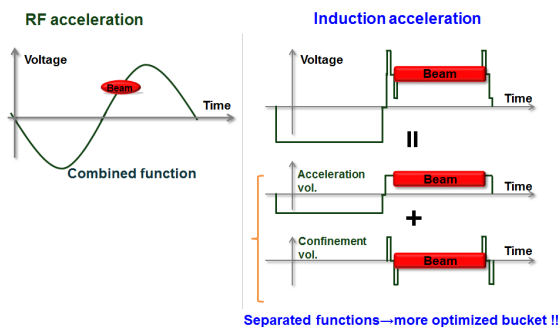

Figure 1: Schematic view of Induction acceleration with the comparison with conventional RF acceleration.

In induction synchrotron, beam acceleration and confinement voltages are separately applied by the induction cells with different excitation pulse shown in Fig. 1. Therefore better optimized beam buckets become feasible.

KEK DIGITAL ACCELERATOR

KEK digital accelerator [4] is a rapid cycling induction synchrotron with repetition frequency of 10 Hz and circumference of 37.7 m. This accelerator is not equipped with RF cavity, but equipped with induction cells. Heavy ion beam generated in ECR ion source which is installed in 200keV platform is directly injected into the ring and accelerated to higher energy.

Switching System of Induction Acceleration

Each induction cell is driven by switching power supply (SPS) shown in Fig. 2. On/Off timings of the solid-state switching element of SPS are controlled at the exact timing in every stage of the acceleration. For this purpose, the fully programmed acceleration control system based on the FPGA has been developed.
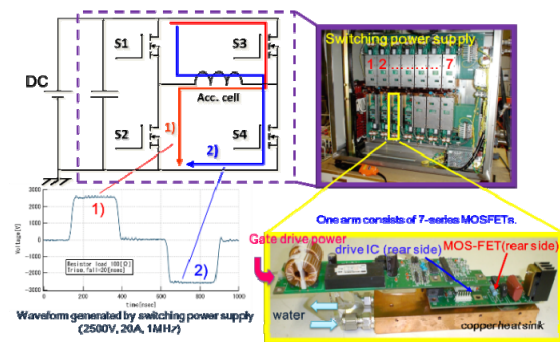

Figure 2: The schematic view of the induction acceleration system.

Fully Programmed Acceleration Control System

ON/OFF of acceleration voltages at induction cells are given by the SPS, through the signals sent from the FPGA, in which these timings are pre-programmed before acceleration. Trigger of the FPGA program and pulse mode ion source is controlled by 10 Hz clock signals, generated by the PLC (Programmable Logic Controller) synchronizing to the ramped magnetic field of the bending magnets $B(t)$ shown in Fig. 3.

At first we specify the ideal magnetic field $B_{control}(t)$ corresponding to actual magnetic field $B_{actual}(t)$ carefully

[5]. $B_{control}(t)$ uniquely determines ideal revolution frequency and ideal required acceleration voltage.
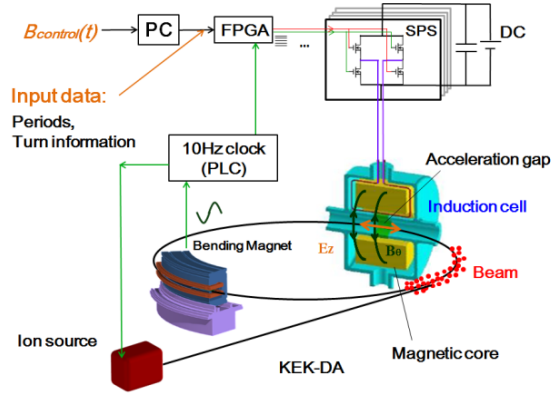

Figure 3: The schematic view of the induction acceleration system.

ACCELERATION AND CONFINEMENT SCHEME

Confinement Voltages: V_{bb}

Trigger timing of confinement voltage pulses is determined from the ideal revolution period in FPGA. Therefore, ideal revolution periods of every turn are stored in the memory of the FPGA in advance.

Confinement voltage pulses are generated every turn. In the present experiment, the length of beam confinement region (beam bucket) is set to be one sixth of the revolution period as shown in Fig. 4.
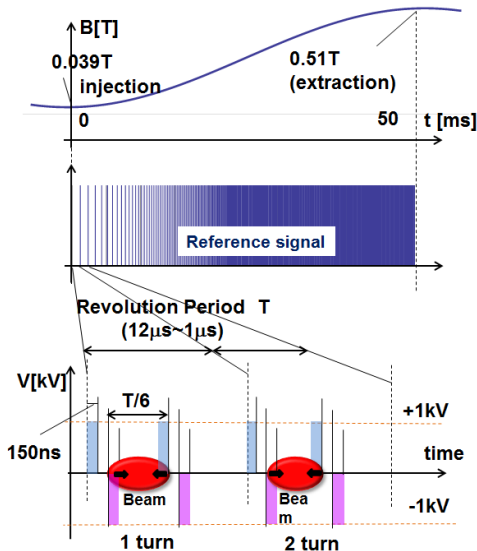

Figure 4: The confinement voltage in every periods.

Acceleration Voltages: V_{acc}

In any circular accelerator, the required–acceleration voltage per turn $V(t)$ is written by

$$V(t) = \rho C_0 \frac{dB(t)}{dt} \qquad (1)$$

where the bending radius ρ is 3.3m, the ring circumference C_0 is 37.7 m, and $B(t)$ is the magnetic flux density of bending magnets. Since the output voltage of the induction cell is constant (V_0) due to the intrinsic nature of the induction acceleration system shown in Fig. 2 and Fig. 3, the pulse density of V_{acc} has to be managed so as to effectively satisfy Eq. (1). In other words, a beam is accelerated in some turns and not accelerated in other turns as shown in Fig. 5. We have introduced a logic that the acceleration pulse are generated when the difference between the sum of the required acceleration voltage from injection and the integrated magnitude of the actually provided acceleration voltage is beyond V_0. The pulse density function $\delta(n)$ that takes 0 for no acceleration or 1 for acceleration. The criterion condition is given by

$$\delta(N+1) = \begin{cases} 1 & \cdots (\sum_{n=1}^{N+1} V(n) - V_0 \sum_{n=1}^{N} \delta(n) > V_0) \\ 0 & \cdots (\sum_{n=1}^{N+1} V(n) - V_0 \sum_{n=1}^{N} \delta(n) < V_0) \end{cases} \qquad (2)$$

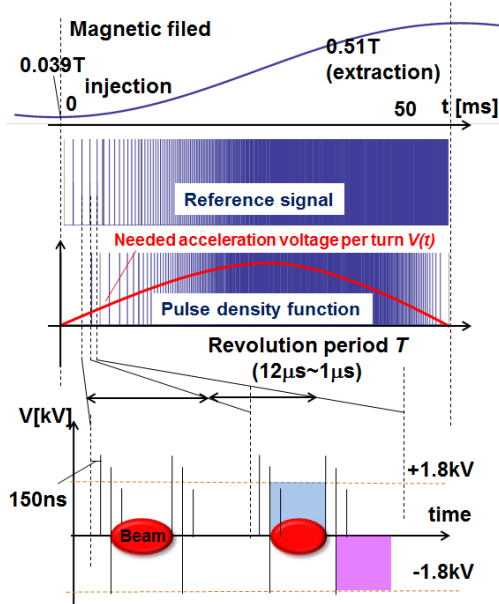These data are loaded into FPGA before starting acceleration.

Figure 5: The acceleration voltages are generated discretely.

EXPERIMENTAL RESULT

$B(t)$ was ramped from 0.039 T to 0.51 T in 50 msec. Ion beam of $A/Q = 4$ was accelerated up to 8 [MeV/u] at the stage of test acceleration experiment. Its projection on the x-y plane is shown in Fig. 6. Beam signals are characterized in the region collared white.
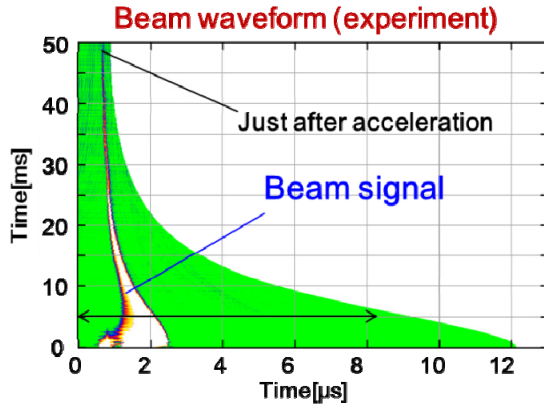
Figure 6: Time-turn plane view of a trapped and accelerated beam signal (experiment).

Confinement voltages V_{bb} are shown in a similar as the beam signal (projection of the mountain view) in Fig. 7. Red and blue ranges depict the positive set voltage pulse of 2 kV and negative reset voltage pulse of –2kV, respectively. The barrier bucket was gradually squeezed from 2 μs to 200 ns, following the revolution frequency. Compared with beam position in Fig. 6, it is found that the beam is well confined by the bucket.
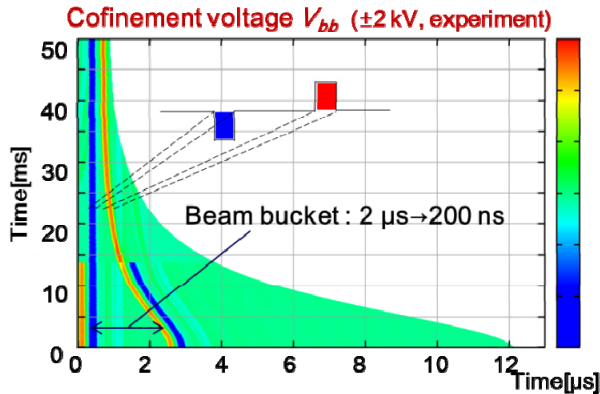

Figure 7: Time-turn plane view of V_{bb} where set pulse (red) and negative reset pulse (blue) (experiment).

On the other hand, the acceleration voltage pulses V_{acc} in Fig. 8 were generated so as to cover the entire beam bucket. This means that beam is accelerated without missing partiles. It is clearly found in Fig. 8 that the density of V_{acc} is sparse near injection and the final stage.
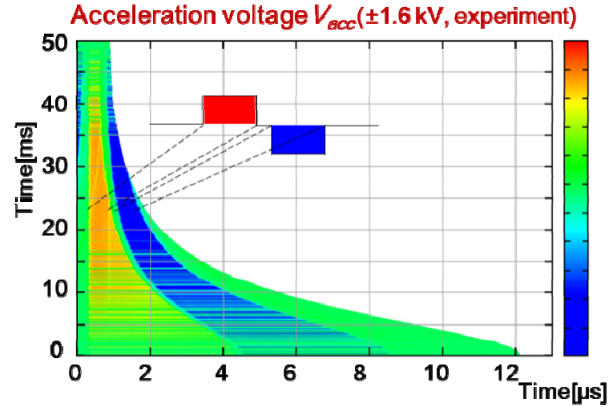

Figure 8: Time-turn plane view of V_{acc} (experiment) where set pulse (yellow) and reset pulse (blue). The pulse density is sparse in the injection and final stage than the medium stage.

Through this experiment, we have confirmed that the ion beam of $A/Q = 4$ was stably accelerated in the fast cycling induction synchrotron with a wide revolution frequency (82 kHz ~ 1 MHz).

CONCLUSION

Heavy ion beam was accelerated over a very broad range of revolution frequency in the KEK digital accelerator. This suggests that an acceleration technique to accelerate any ion species with any charge state has been established in principle.

ACKNOWLEDGMENT

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