KEK DIGITAL ACCELERATOR AND RECENT BEAM COMMISSIONING RESULT*

K.Takayama*, T.Adachi, T.Arai, D. Arakawa, E.Kadokura, T.Kawakubo, T.Kubo, H.Nakanishi, K.Okamura, H.Someya, A.Takagi, and M.Wake, KEK, Tsukuba, Ibaraki Japan
Leo Kwee Wah, Graduate University of Advanced Studies, Hayama, Kanagawa Japan
LIU Xingguang and T.Yoshimoto, Tokyo Institute of Technology, Nagatsuda, Kanagawa, Japan
Y.Barata and S.Harada, Tokyo City University, Todoroki, Tokyo, Japan
H.Asao and Y.Okada, NEC Network-Sensor, Futyu, Tokyo, Japan
T.Iwashita and K.Okazaki , Nippon Advanced Technology Co. Ltd. (NAT), Tokaimura, Japan

Abstract

The early beam commissioning of the KEK digital accelerator, which consists of novel accelerator components such as a permanent magnet x-band ECRIS, an Einzel lens longitudinal chopper, an electrostatic injection kicker, and induction acceleration devices, is reported here. Performance of the Einzel lens longitudinal chopper is described. Results of beam commissioning, such as the beam orbit correction, barrier bucket bunch capture, and induction acceleration are described.

INTRODUCTION

The KEK digital accelerator (DA) is a small-scale induction synchrotron (IS) without a high-energy injector [1]. The concept of an IS was experimentally demonstrated in 2006 [2] by utilizing the KEK 12 GeV PS. Instead of an RF cavity, an induction cell is employed as the acceleration device. It is simply a one-to-one transformer, which is energized by a switching power supply generating pulse voltage. Two types of induction cells for acceleration and confinement are employed. It is a crucial point of the IS that voltage timing is controlled by a gate signal of solid-state switching elements based on bunch signals detected at the bunch monitor. This operational performance enables acceleration of ions from extremely low velocities, and is the reason why the DA does not require a high-energy injector. It is understood from these properties that the DA is capable of accelerating any species of ion, regardless of possible charge state.

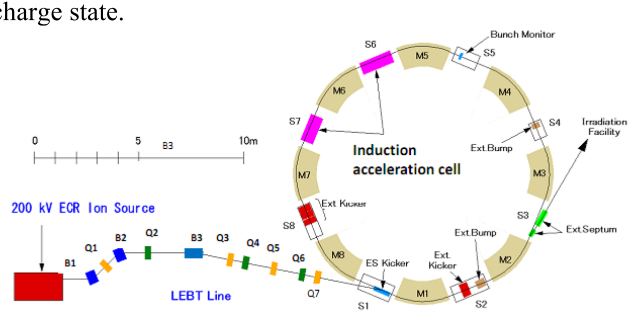

Figure 1: Outline of the KEK Digital Accelerator.

In the KEK DA, schematically shown in Fig. 1, a 5 msec long ion beam is created in the electron cyclotron resonance ion source (ECRIS) and chopped by the newly developed Einzel lens chopper in 5 μsec and post-accelerated in the acceleration column attached with the 200 kV high-voltage terminal (HVT), after which it propagates through the low-energy beam transport line (LEBT) to be injected into the ring with the electrostatic injection kicker. The electrostatic kicker voltage is turned off before the injected beam pulse completes a single turn in the DA ring, which is a rapid-cycle synchrotron. The injected beam is captured with a pair of barrier voltage pulses and accelerated with pulse voltages, the pulse length and amplitude of which are controlled in digital. He1+ ions beam commissioning in the KEK-DA is described here.

* takayama@post.kek.jp

MACHINE

Permanent Magnet ECRIS [3]

The ECRIS is embedded on the DC 200 kV high voltage platform. In order to minimize the consumed electric power and avoid troublesome of water cooling on the high voltage platform, the permanent magnet ECRIS being operated in the pulse-mode (10 Hz and 2-5 msec) has been developed. This ECRIS driven by a 9.35 GHz TWT with a maximum output power of 750 W is capable of producing from hydrogen ion to Argon ion, which are extracted at 10-14 kV. The HVT including the Einzel lens chopper and the post-acceleration column is schematically shown in Fig.2.

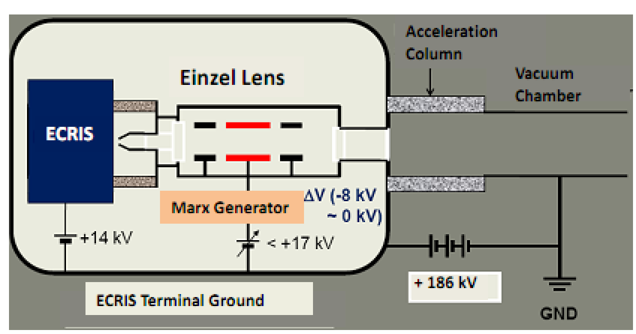

Figure 2: Schematic of the HVT and its contents.

Einzel Lens Chopper[4]

As stated in the above introductive part, the revolution time-period of ions in the KEK-DA is around 10 μsec. The single-turn injection scheme requires a pulse length less than 10 μsec. A pulse chopper upstream is necessarily demanded. There are several possible schemes for a chopper. Is it a high energy type or low energy type? Is it a transverse type or longitudinal type? Beam-handling at a low energy stage is apparently preferable, leading to low yields of secondary electrons, small out-gassing, and low energy X-ray emission. Another important factor is its low cost. Careful considerations on a possible space and discharge in the high voltage post acceleration column and quality of chopper voltage have motivated us to develop the Einzel lens chopper, which works as a longitudinal chopper and demands only an additional power supply to control the gate voltage. The chopper head is the Einzel lens middle electrode which is necessary for transverse orbit matching. To realize a fast pulse rising and falling time of the chopped pulse, the solid-state switch driven Marx generator has been developed. A 5 μsec-long pulse of minus 6 kV generated by the Marx generator is superimposed on DC 17 kV of the middle electrode, which prevents ions to propagate downstream except for the gating time-period. The chopped pulse is immediately post-accelerated in the DC acceleration column of 186 kV to enter into the momentum selector or charge-state selector region. Figure 3 shows the 5 μsec pulses chopped at the timing of 0.4 msec from the pulse head respectively, which were measured by a Faraday cup. The rising and falling time are determined by the circuit parameters of the diagnostics circuit system including the stray capacitance of FC. The reconstructed chopped pulse shape is known to be very sharp.

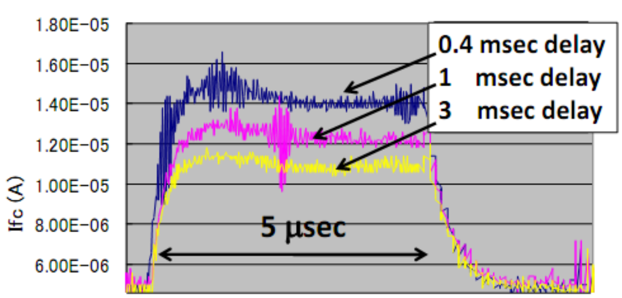

Figure 3: 5 μs chopped pulse profiles, which are chopped at different times from the pulse head of a 5 ms ion pulse.

Low Energy Beam Transport (LEBT)

The LEBT consists of the momentum selector magnet (or charge state selector), other two bending magnets, 7 focusing quadrupole magnets, a few beam profile monitors, and additional steering magnets, the last four magnets (STH3,4 and STV3,4) of which are used for the purpose of injection error correction.

Ring Lattice

The lattice consists of eight combined-function (FDF) magnets (M1~M8) symmetrically placed along the beam orbit. Eight straight sections are occupied by the electrostatic injection kicker (S1), extraction kicker (S2,S8), extraction septum magnets (S3), induction acceleration cells for beam confinement and acceleration (S6, S7), and vertical orbit correction magnets (S4, S5), position monitors (S2, S4, S5, S8), movable screen.monitor (S1), and bunch monitor (S5) Lattice/beam parameters are listed in Table 1.

Table 1: Lattice/beam parameters

Circumference	C_0	37.7 m
Bending radius	ρ	3.3 m
Maximum B	B_{max}	0.84 Tesla
Bet. tune in x/y	Q_x/ Q_y	2.17 - 2.09/2.30 - 2.40
Transition energy	γ_T	2.25
Energy (Inj.)/ nucleon	E_{inj}	200 keV(Q/A)
Rev. frequency	f	~80 kHz – 3 MHz

Electrostatic Injection Kicker [5]

From a simple reason that for handling of low velocity ions electrostatic fields are much suitable, the electrostatic injection kicker has been employed. Before the injection, two 80 cm long parallel plates are excited to 20 kV through a pulse forming network line, which is required to counter the injection angle of 11.25 degree. To ensure the field uniformity among two plates, one of which is grounded, three interim electrode panels are inserted. Before the ion pulse completes its first turn, the high voltage is turned off by firing thyratrons, which allow charges on the capacitance including the electrode plates to quickly flow to the ground through the register. Actually the electrostatic kicker voltage was tuned off in a few μsec with dumped back-and force reflection noises.

BEAM COMISSIOING

Beam Orbit

Betatron motions of an injected bunch centroid caused by injection errors were observed by the diagonal electrostatic position monitor in both directions. It turned out that betatron tunes are close to the design values. The injected He1+ ion bunch performed free-circultion in the KEK-DA at the injection fields of B_{min}=390 Gauss and injection optics was optimized by adjusting excitation currents of the steering magnets placed just before the injection point (see Fig.4). The off-set seen in Fig.4, which is left unchanged even after the injection correction is the closed orbit distortion (COD) at the observing position $s=sM$.

The KEK-DA is expected to accelerate ions from the quite low energy. Therefore, the magnetic fields of the main magnets at injection are very low as shown in Table 1. At this field level, their remnants fields are relatively large; they should become potential orbit-error sources. Actually we have tried to measure remnant fields at the localized sampling position in the limited area on the pole face. Their magnitudes scatter from 5 Gauss to 10 Gauss [6].

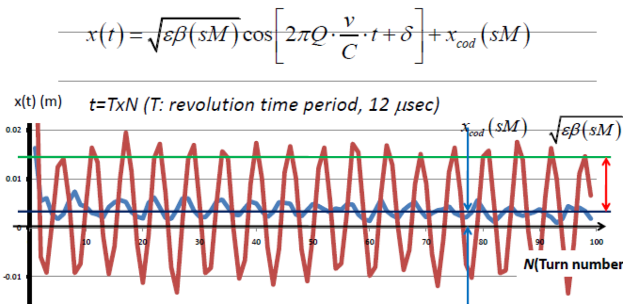

Figure 4: Motion of the beam center: with injection error (brown) and with correction (blue), observed at some position monitor.

The COD, which is a periodic function of *s* with the periodicity of *C*, has been observed at 5 points along the ring. These data are not enough to recognize its whole profile over the ring. In general, it is known that the COD resulting from random errors is dominated by the harmonic components close to the betatron tune, that is, 2. So, the observed data have been fitted by the 1st and 2nd harmonics. It is shown in Fig.5. Correction of the fitted COD was tried. For this purpose, 8 figure back-leg coils have been prepared (see Fig. 6). A back-leg coil is wound so as to oppositely encircle the return cores of a pair of every next main magnets. This winding figure is crucial to correct the 2nd harmonic component of the COD and to avoid the voltage induced on the power supply for the back-leg coil when the main magnets ramp. The fitted COD was corrected with four independently excited correction currents, which were obtained by mathematically solving the algebraic correction equation. The result is shown in Fig.5. The COD changed its shape as expected at the observing points. Certainly the peak value was substantially reduced, however, the 3rd harmonic became visible. At the next step this 3rd harmonic component will be corrected.

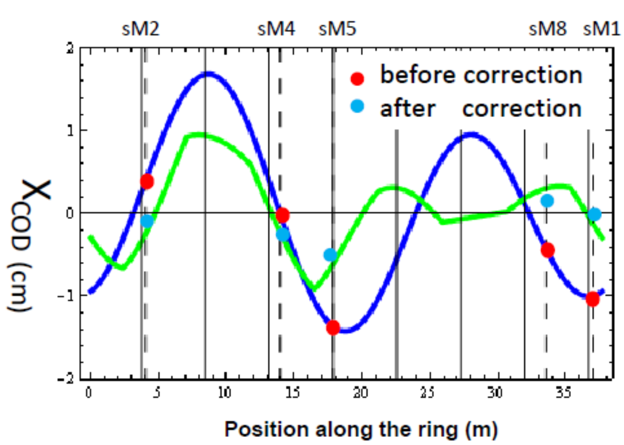

Figure 5: Discretely observed data (red point) of the COD without correction, its 1st and 2nd harmonics fitted shape (blue line), observed data (sky blue point) with correction, and its fitted shape (green).

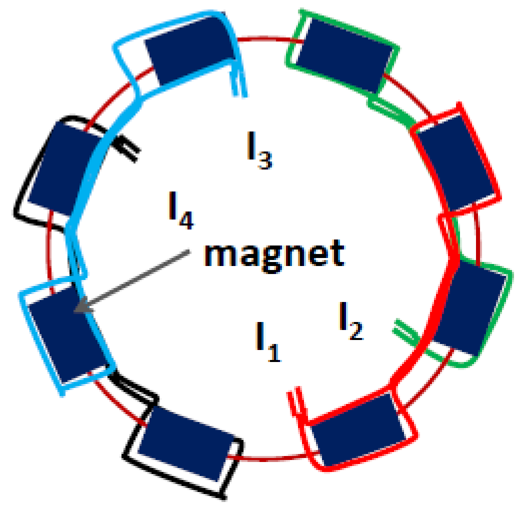

Figure 6: COD correction system with four 8 figure back-leg coils excited by independent power sources.

Free Circulation in the Ring

The injected bunch circulating in the ring without any longitudinal control has been observed by the bunch monitor (see Fig.7).

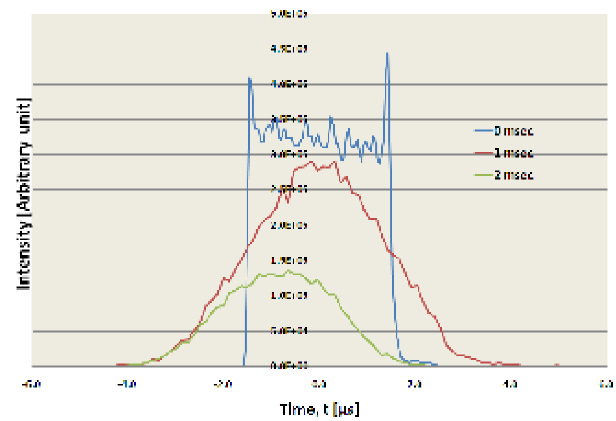

Figure 7: Bunch profiles at the 1st turn and 1 msec and 2 msec (measurement).

Mountain views in the time spaces and their projection on the time-turn plane as seen in Figs.8a,b are quite useful for this purpose. Gradual diffusion in the time or on the orbit coordinate indicates a momentum spread of the injected bunch. Meanwhile, something like compression at the early stage of free circulation is visible. This suggests that the injected bunch has a negative momentum spread in the bunch head and a positive momentum spread in addition to an intrinsic momentum spread. It turns out that the seed of this abnormal distribution in the phase space is created as transient effects in the chopper pulse shape and a kind of drift compression takes place during free run in the ring (see Fig.9) [7]. In addition, it has been observed that the speed of compression depends on the beam intensity [8].

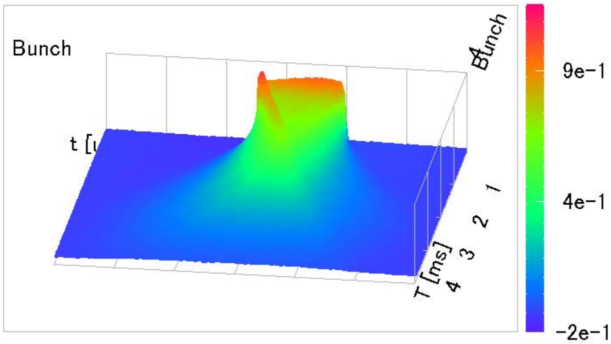

Figure 8a.: Typical mountain view of a bunch profile.

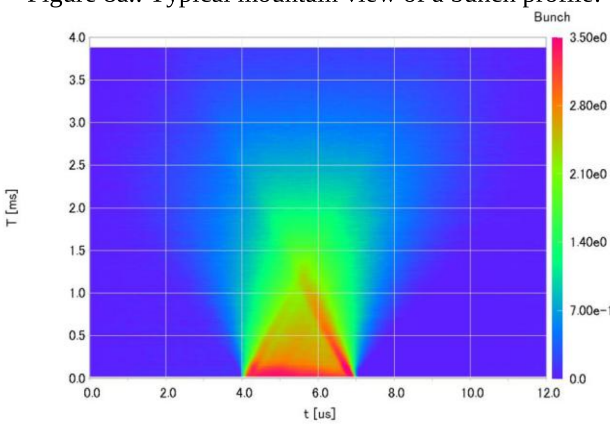

Figure 8b: Projection of the mountain view on the time-turn plane.

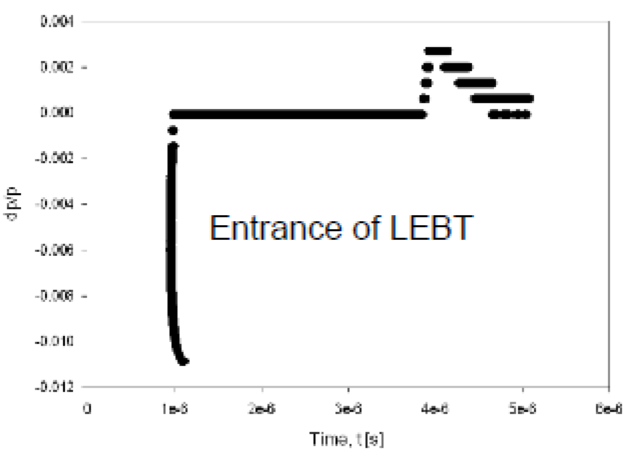

Figure 9: Phase space plot just after the HVT (simulation).

Barrier Bucket Trapping

At the injection energy, various barrier bucket trapping experiments were conducted. A He1+ bunch was trapped by the barrier voltages that were triggered at the revolution frequency and had a short time duration. Fig.10 shows that a short fraction corresponding this time duration is trapped. Two barrier buckets were generated in one revolution period. As expected, two parts of the injected pulse were captured (See Fig.11). A barrier bucket was created with a sufficiently long width to accommodate the injection pulse. It is shown in Fig. 12 that the captured beam pulse survives through 1 acceleration time period of 50 msec.

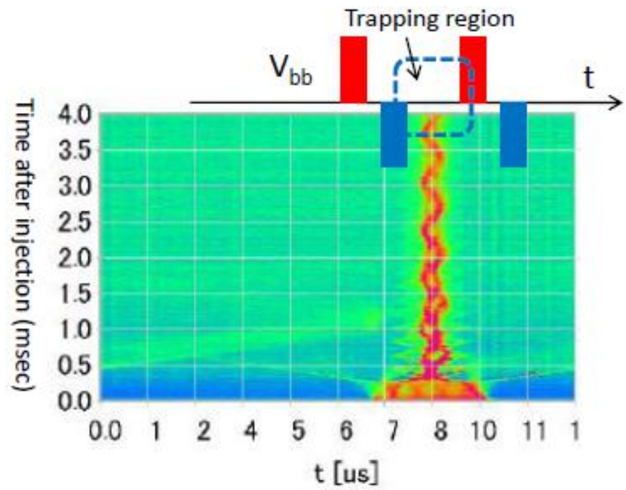

Figure 10: Trapping of a small fraction by the barrier voltages with a short time duration.

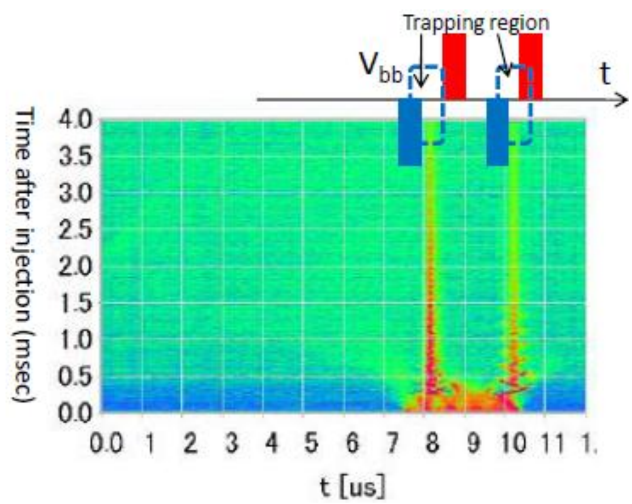

Figure 11: Trapping of two parts of the injected pulse by twin pair of barrier voltage pulses.

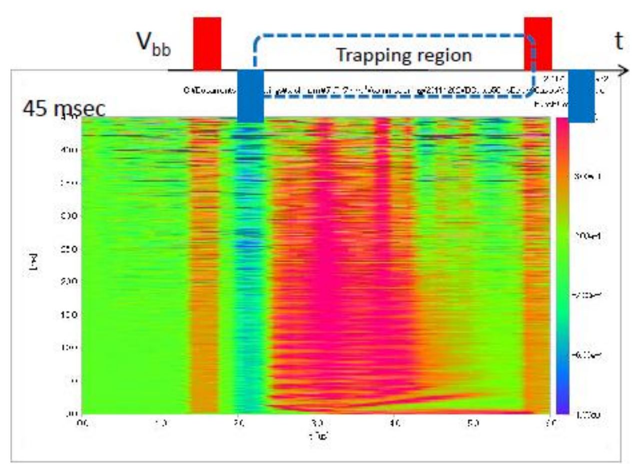

Figure 12: Trapping of a full width of the injected pulse.

Barrier Bucket Handling (Bunch Squeezing)

Barrier bucket handling of a long bunch, which can't be realized in an RF bucket, has been expected from early days of induction synchrotron R&D [2]. This was demonstrated by using the present He1+ bunch at the fixed energy. Bunch profiles on the process of bunch squeezing, where the trigger timing for the right barrier voltage pulse is discretely changed by 8 nsec per turn from 0 msec to 7 msec, are shown in Fig. 13. Mountain view of the bunch profile in the same experiment, which delineates typical features of the barrier bucket bunch trapping, is shown in Fig. 14. This experimental result seems to reflect a motion of a bunch injected with an extremely small momentum spread less than 0.025 % and an energy deviation of +0.23 % in the longitudinal phase space. The bunch tail moves forward and a part of the originally bunch head moves backward. Both encounter at 1.5 msec after injection. The latter is reflected by the moving barrier-voltage pulse. The bunch never expands beyond this barrier voltage pulse-edges. Beyond 7 msec, the barrier bucket is fixed. Slightly diffusing of the bunch into the upper region can be attributed to increasing of the momentum spread associated with bunch squeezing.

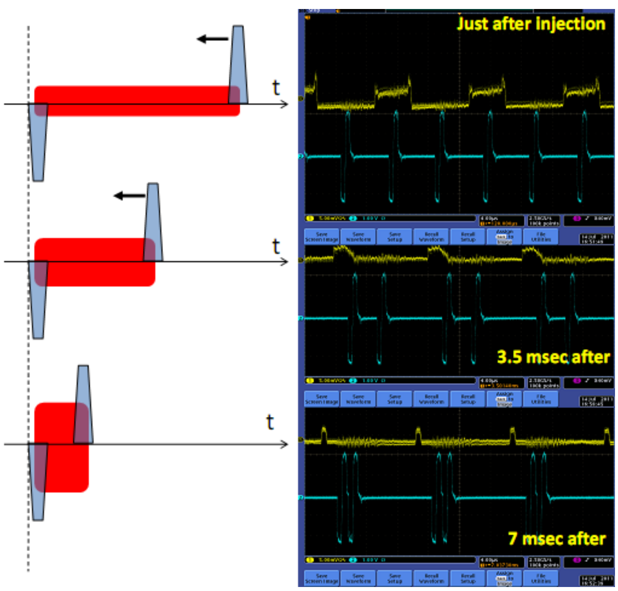

Figure 13: Bunch squeezing experiment (right) and schematic of barrier voltage operation (left).

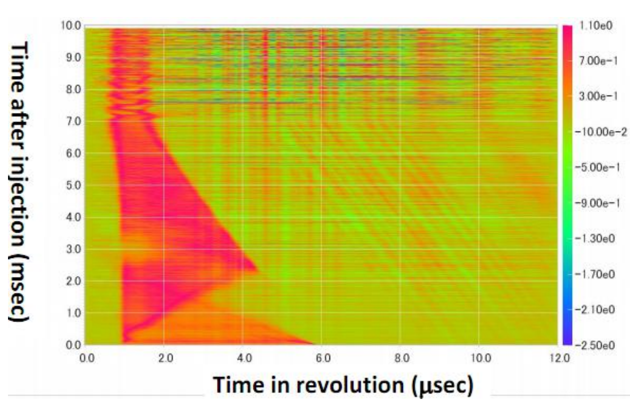

Figure 14: Projection of the mountain views of the bunch profile on the squeezing process.

Acceleration

At the early stage, the beam orbit was not corrected because all existing monitors didn't work due to primitive reasons, such as poor S/N ratio and circuit short. On the other hand, the acceleration control code for the employed FPGA were under development. Nevertheless, induction acceleration was carried out. The injected beam was accelerated up to 42 msec, reducing its intensity; in other ward, it corresponds to 12 MeV. Preliminary results are shown in Fig. 15.

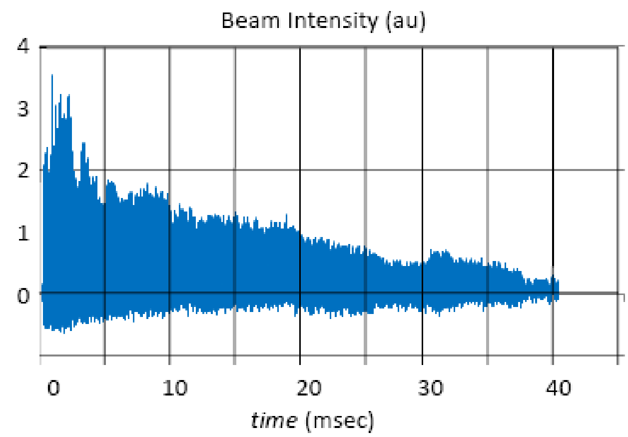

Figure 15: Result of induction acceleration up to 42 msec, corresponding 12 MeV for He1+.

SUMMARY

We have successfully demonstrated the injection operation of the KEK-DA and barrier bucket beam-handling using He1+ ion beams. The preliminary acceleration has been demonstrated. What we have observed seem to be within our expectation. Hereafter, the induction acceleration under the well managed way will be continued beyond the present stage. From this fall, heavy ion beams will be delivered to users, laboratory experiments for Space Science.

ACKNOWLEDGMENT

Work supported by a Grant-In-Aid for Scientific Research (A) (KAKENHI No. 23240082)

REFERENCES

[1] T. Iwashita *et al.*, "KEK Digital Accelerator", *Phys. Rev. ST-AB 14*, 071301 (2011).
[2] K. Takayama *et al.*, "Experimental Demonstration of the Induction Synchrotron", *Phys. Rev. Lett.* **98**, 054801-4 (2007), "Induction Accelerators", K.Takayama and R.Briggs (*Eds.*) (Springer, 2010).
[3] Leo Kwee Wah *et al.*, "Permanent Magnet ECRIS for the KEK Digital Accelerator", *19th Int. Workshop on ECRIS*, August 23-26, Grenoble, France, TUPOT15 (2010).

[4] T.Adachi, T.Arai, K.W.Leo, K.Takayama, and A.Tokuchi, "A Solid-state Marx Generator driven Einzel Lens Chopper", *Rev. Sci. Inst.* **82**, 083305 (2011).
[5] T. Adachi, T. Kawakubo, and T. Yoshii, "Injection and Extraction for the KEK Digital Accelerator", in Proc. of IPAC'10, p.570-572 (2010).
[6] K.Takayama, T.Adachi, E.Nakamura, and H.Someya, "Beam Dynamical Issues of The KEK All-Ion Accelerator", EPAC2008, THPC107.
[7] K.W.Leo, Dr. Thesis, to be published (2012).
[8] X.Liu *et al.*, "Longitudinal Beam Motion in the KEK Digital Accelerator: Tracking Simulation and Experimental Results", in this conference.