THE EINZEL LENS LONGITUDINAL CHOPPER

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Abstract

This paper describes the Einzel lens beam chopper that has been newly developed for the KEK digital accelerator (DA) project. Function of beam chopping is added to the Einzel lens used as a transverse focusing device for a low energy ion beam. Its idea and operational chopping performance are discussed in details.

INTRODUCTION

The KEK digital accelerator (DA) is a small-scale induction synchrotron without a high-energy injector [1]. The concept of an induction synchrotron was experimentally demonstrated in 2006 [2] by utilizing the KEK 12 GeV Proton Synchrotron. 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. An injected beam pulse is captured by the barrier bucket and accelerated with pulse voltages. It is a crucial point of the induction synchrotron 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.

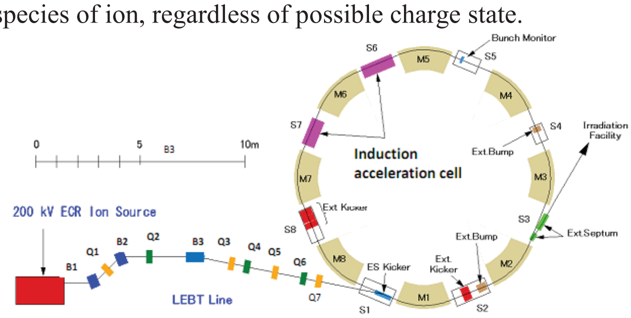

Figure 1: Outline of the KEK Digital Accelerator.

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 platform (HVP), 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.

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The single turn injection scheme limits on the maximum beam length. On the other hand, beam production in most of ion sources requires a finite time period due to a principle mechanism of plasma formation. A beam chopper which can provide a desired pulse length is indispensable. In this paper, its main argument will be focused on how a necessary beam length can be generated and key features of its operational performance are summarized.

ACCELERATOR COMPLEX

Permanent Magnet ECRIS [3]

The ECRIS is embedded on the DC 200 kV HVP. 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 kV. The HVP including the Einzel lens chopper and the post-acceleration column is schematically shown in Fig.2.

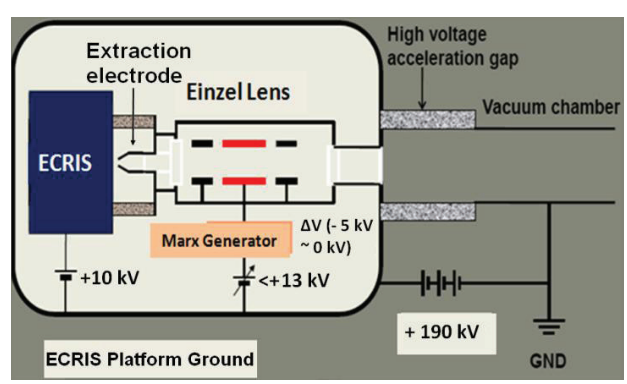

Figure 2: Schematic of the HVT and its contents.

Einzel Lens

The Einzel lens is located just after the ECRIS extraction electrode. Its middle electrode is sustained at an optimized voltage, which gives over-all transverse

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matching downstream. As described in details later, a function of beam chopping is added to this Einzel lens.

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.

Accelerator Ring

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

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. 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.

LONGITUDINAL CHOPPER

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 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. Its conceptual idea is depicted in Fig.3.

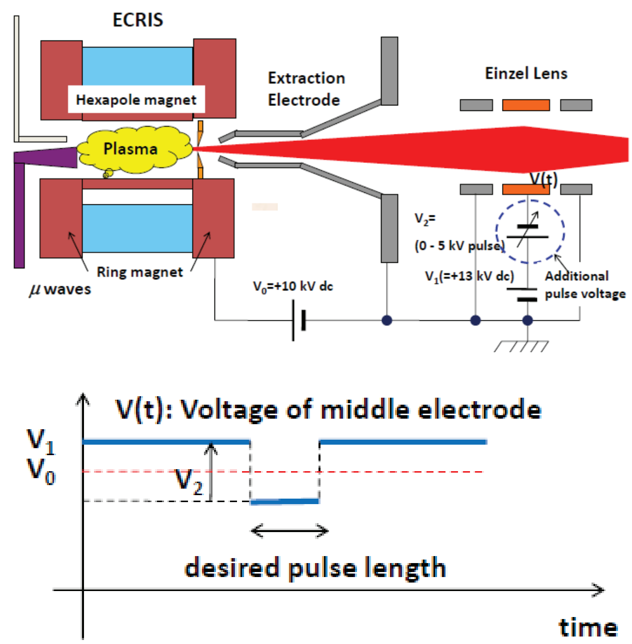

Figure 3: Idea of the Einzel lens chopper (upper) and Voltage profile of the Einzel lens V(t) (bottom).

In order to confirm the idea, IGUN simulations have been performed. The simulation results give us the necessary blocking voltage as well as the matching voltage. Figure 4 shows typical ion beam traces nearby the Einzel lens a s a function of V(t).

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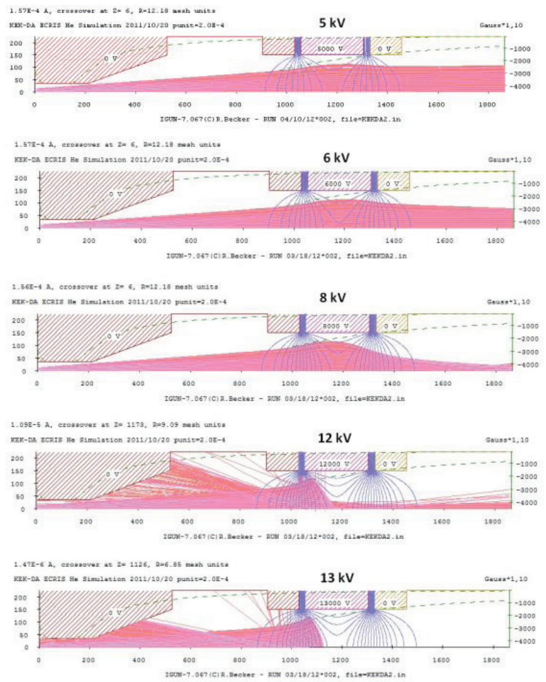

Figure 4: IGUN simulations for different Einzel lens voltages.

In addition, this prediction has been confirmed by experiments, where the current of ion beam is observed 2.5 m downstream by the Faraday cup for the different static Einzel lens voltages. The results are shown in Figure 5, which is fairly in good agreement with the simulation results.

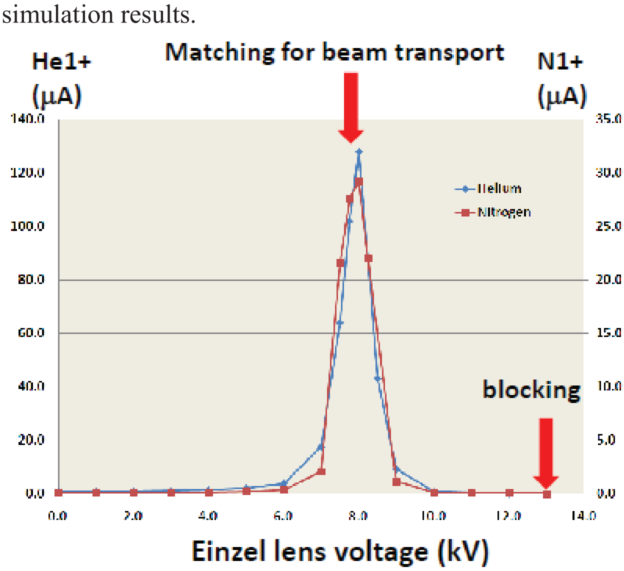

Figure 5: Beam Current for He1+ and N1+ vs. Einzel lens voltage.

To realize a fast pulse rising and falling time of the chopped pulse, the solid-state switch driven Marx generator has been developed. Expecting fast rising/falling in the pulse voltage, MOSFET devices have been employed as a switching element. The equivalent circuit is depicted in Figure 6 together with its photograph.

Pulse profiles are shown in Figure 7, where one can realize a good agreement between the SPICE simulation and observed result.

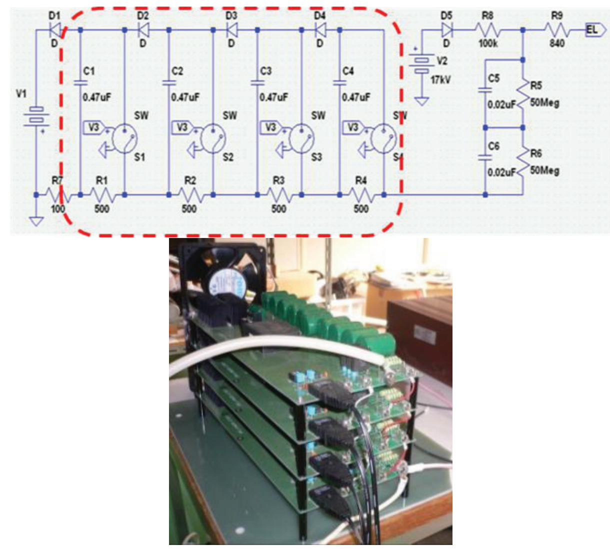

Figure 6: Equivalent circuit of the Marx generator and its photo.

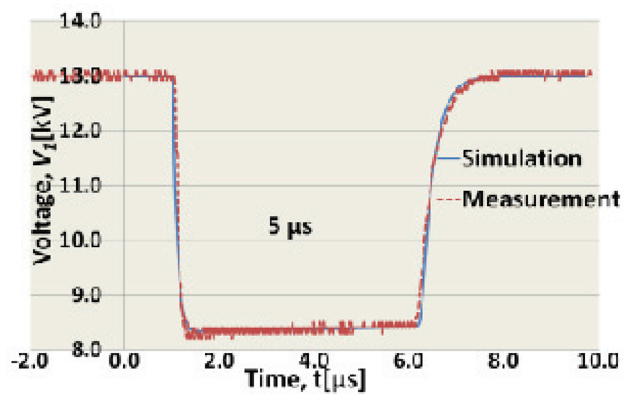

Figure 7: Pulse voltage for chopper performance.

A 5 µsec-long pulse of minus 5 kV generated by the Marx generator is superimposed on DC 13 kV of the middle electrode, which prevents ions to propagate downstream except for the gating time-period, as explained in Figure 3. The chopped pulse is immediately post-accelerated in the DC acceleration column of 190 kV to enter into the momentum selector or charge-state selector region.

Figure 8 shows the 5 µsec pulses chopped from the 5 msec He1+ beam at the timing of 0.4 and 3 msec from the pulse head respectively, which were measured by a Faraday cup (FC). The rising and falling time are determined by the circuit parameters of the diagnostics circuit system including the stray capacitance of FC.

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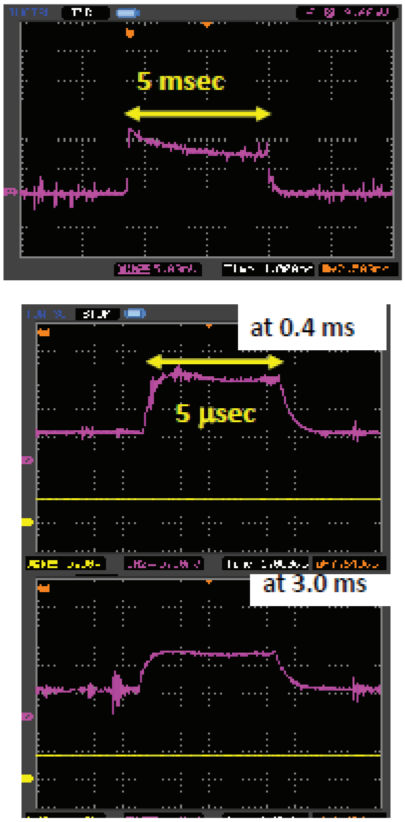

Figure 8: 5 μs chopped pulse profiles, which are chopped at different times from the pulse head of a 5 ms ion pulse.

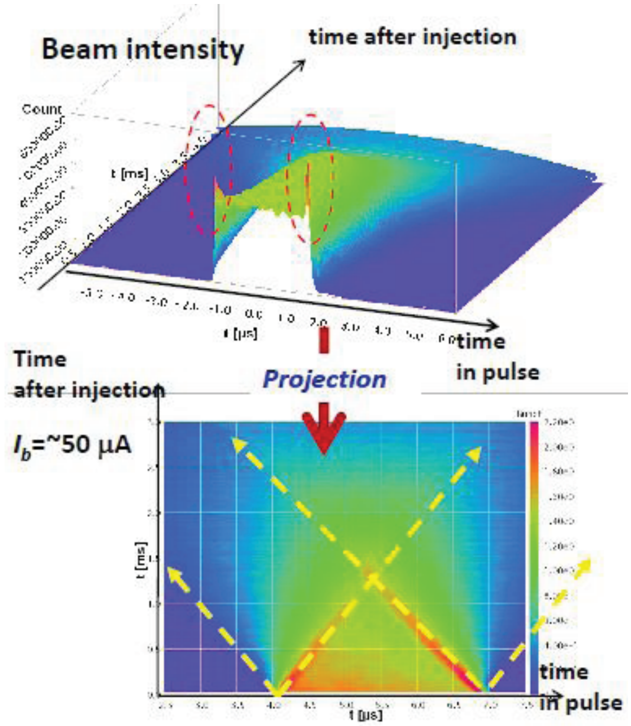

Figure 10: Mountain view of the freely circulating chopped pulse (top) and its projection on the time-turn plane (bottom).

QUALITY OF CHOPPED BEAM

Quality of a chopped beam is of our big concern. Especially, the longitudinal emittance of the chopped beam is an important parameter to capture in the barrier bucket of the digital accelerator. A distribution of chopped ions in the momentum space is crucial to determine the longitudinal emittance. In order to know precise information of the injected ion beam, a behaviour of free circulation in the ring has been carefully observed.

Free Circulation in the Ring

The injected bunch circulating in the ring without any longitudinal control has been observed by the bunch monitor. Mountain views in the time spaces and their projection on the time-turn plane as seen in Fig. 10 are quite useful for the present purpose. Sharp peaks at both edges of the injected pulse are notable.

Figure 10 strongly indicates that the injected beam pulse has a multiple momentum spectrum. Gradual diffusion in the time or on the orbit coordinate suggests 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 is suggested that the seed of this abnormal distribution in the phase space is created as transient effects in the chopper pulse shape. This view has motivated extensive studies to explore what happens in propagating through the chopper region [5,6].

Simulation

A macroparticle simulation code to analyze the particle motion in the longitudinal direction was written. The simulation has manifested that a large momentum deviation occurs at pulse head and tail timing, taking into account the temporal change in the chopper voltage pulse (see Fig.7). A typical example is shown in Fig. 11.

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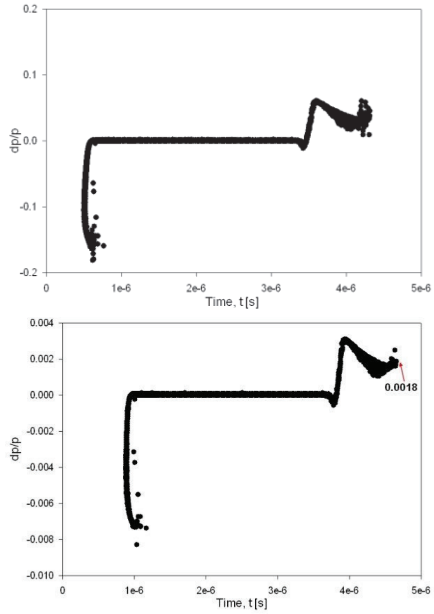

Figure 11: Phase space plot just after the Einzel lens (top) and the post acceleration column (bottom), where a relative momentum deviation is largely reduced due to acceleration from 10 keV to 200 keV, ($\Delta p/p$)=(-0.16)(10keV/200keV)=--0.008.

Since these momentum deviation survives even after injection into the ring, it turns out that the observed phenomena is understandable. Diffusion speed in the time-turn plane is consistent to the prediction from the momentum deviation observed in Fig. 11.

Physics Behind

This momentum deviation is qualitatively explained with the following simple model. Let consider three particles which enter into the gaps of the EL during a flat voltage region and the transient time regions that are depicted as colour zones in Fig.12. Magnitude of electric fields, E_1 and E_2 exerting on the particles at two gaps is different due to a finite transit time of a particle. This difference leads to the momentum deviation, that is,

for particle A, $|E_1|>|E_2|$, then $\Delta p/p < 0$,
for particle B, $|E_1|=|E_2|$, then $\Delta p/p = 0$,
for particle C, $|E_1|<|E_2|$, then $\Delta p/p > 0$.

This type perturbation on the momentum space is an intrinsic nature of the longitudinal chopper, where a rectangular pulse shape is not expected even if its net size can be reduced by improving the rising/falling time. The rising and falling time depends on a stray capacitance of the EL. Reducing of the stray capacitance as small as possible is effective to minimize the momentum deviation. The present magnitude of $(\Delta p/p)_{max}$~ 0.1% is still small and acceptable to the barrier bucket and the momentum aperture in the DA.

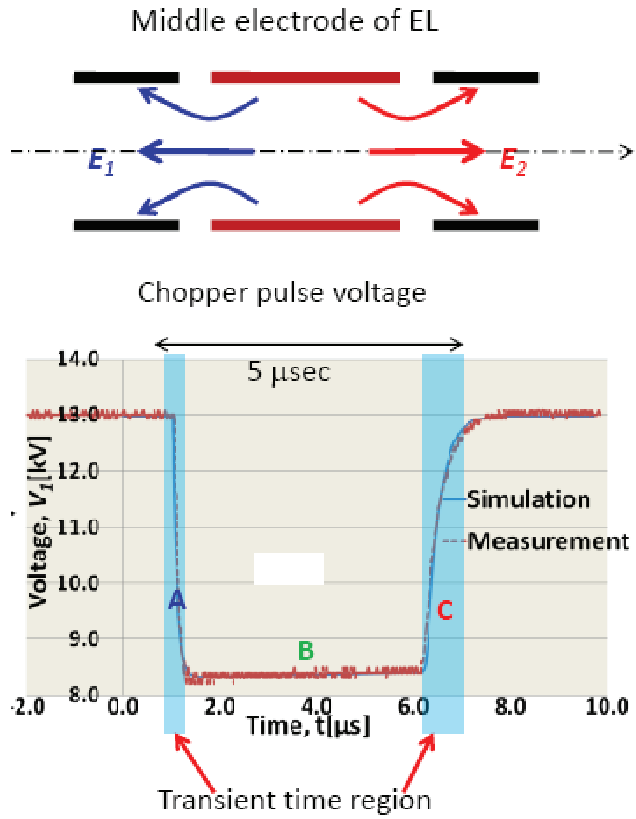

Figure 12: Model of the EL (top) and Typical chopper pulse with transient regions (bottom).

SUMMARY AND PERSPECTIVE

Intrinsic features in the operational performance of the noble longitudinal chopper have been described. The device has been operated more over one and half a year without any trouble. The system is quite reliable. Any required chopper length can be easily provided by simply changing gate timing of the MOSFETs for the Marx generator. It is noted that a whole story has been given in Reference 6. In the near future the EL chopper will be integrated with a laser ablation ion source under development in the collaboration between KEK, BNL, and RIKEN.

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