SOLID-STATE MARX GENERATOR DRIVEN EINZEL LENS CHOPPER*

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Abstract

A new type of pulse chopper called an Einzel lens chopper is described. An Einzel lens placed immediately after an electron cyclotron resonance ion source is driven by high-voltage pulses generated by a newly developed solid-state Marx generator. A rectangular negative barrier pulse-voltage is controlled in time, and the barrier pulse is turned on only when a beam pulse is required. The results of successful experiments[1] are reported herein.

INTRODUCTION

The KEK digital accelerator (DA) is a small-scale induction synchrotron (IS) without a high-energy injector [2]. The concept of an induction synchrotron was experimentally demonstrated in 2006 [3, 4]. In the KEK DA, schematically shown in Fig. 1, an ion beam is created in the electron cyclotron resonance ion source (ECRIS) [5], focused by the Einzel lens, and post-accelerated with the acceleration column in the 200 kV high-voltage terminal (HVT), after which it propagates through the low-energy beam transport line to be injected into the ring with the electrostatic kicker. The electrostatic kicker voltage is turned off well before the injected beam pulse completes a single turn in the DA ring. Thus, the pulse length should always be shorter than the revolution period of the ion beam (~10 μs). This is the reason why the KEK-DA requires a pulse chopper. Thus far, different types of pulse choppers have been developed for similar purposes at other accelerator facilities. Most of them achieve their purpose by transversely deflecting a charged beam in a desired time interval. Since the unwanted and deflected beam, which carries a certain energy given upstream, hits the surface of a vacuum chamber, generation of secondary particles or X-rays is unavoidable.

In an ideal situation, unnecessary ions from the pulse should lose most of their kinetic energy to return to a cloud of neutral atoms and to eventually become subject to evacuation, or should hit the vacuum surface with an energy as low as possible, thus notably reducing X-ray emission and out-gassing from the surface. The concept of an Einzel lens chopper has been proposed in this context, and the Marx generator has been developed to drive the chopper with a rectangular pulse voltage. The idea behind an Einzel lens chopper driven by a solid-state Marx generator and the essential feature of the solid-state Marx generator of the key device are described and experimental results are presented here.

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The Einzel lens itself is a necessary device for matching the transverse beam to the downstream beam guiding system including the post-acceleration region. It is emphasized that an Einzel lens placed immediately behind the ECRIS is a beam-handling device that operates in the region of minimal energy. The utilization of an Einzel lens as a chopper does not require any additional devices at the downstream beam line. A longitudinal chopper determines the rise/fall time of a chopped pulse. Gating in a finite time interval induces velocity dispersion in longitudinal direction, resulting in a difference in the time of flight. This mechanism leads to a distortion in the pulse profile downstream. However, high-voltage DC post-acceleration takes place immediately behind the Einzel lens in the proposed setup. As a result, the time of flight never evolves, and the sharp pulse profile can survive until injection into the KEK-DA.

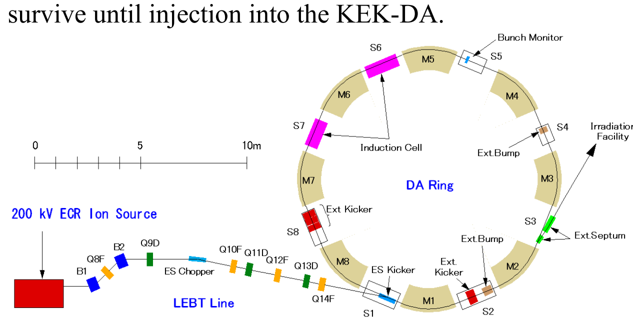

Figure 1: Outline of the KEK Digital Accelerator

ECRIS AND EINZEL LENS

A set of an ECRIS and an Einzel lens following it is shown in Fig. 3. This set is embedded in a high-voltage terminal with an acceleration column of 200 kV. A DC voltage of V_0 is added at its extraction gap. Beyond the extraction gap, the ion beam enters the Einzel lens region. For downstream transverse matching, the middle electrode is maintained at V_1 ($V_1 < V_0$) and both side electrodes are maintained at ground potential in the HVT, respectively. The voltage difference between electrodes is accompanied with electric fields in radial direction, leading to net focusing forces on the ion beam.

Since the KEK-DA is operated at 10 Hz, the ECRIS is operated at the same repetition rate. This operation mode enables the ECRIS to be operated without water cooling. Due to the fundamental ionization mechanism in an ECRIS, a few milliseconds is required for high charge state ions to build up and achieve a steady state. This time interval is 1000 times longer than the required pulse length of 5 μs in the KEK-DA. Thus, 1/1000 of the ion beam pulse extracted from the ECRIS must be chopped. In general, chopping of an ion beam with a lower energy is considerably easier. It is desirable to realize such chopping in the HVT before the ion beam passes thorough the high-voltage acceleration column shown in Fig. 2. This is achieved by introducing a rectangular negative pulse voltage in the Einzel lens. The idea is rather simple. The potential in the central region of the middle electrode of the Einzel lens is maintained at V_0. From the energy conservation law, ions stop at the position of the middle electrode and are unable to propagate downstream. Then, it is of interest to explore the effects of applying a rectangular negative voltage pulse ΔV ($V_0+\Delta V < V_0$) on the middle electrode for a finite time duration τ. When the barrier voltage that stops ions from propagating in longitudinal direction is reduced, ions can propagate beyond the Einzel lens region during τ. This is the essential mechanism of the Einzel lens chopper. It can be described in terms of "longitudinal gating".

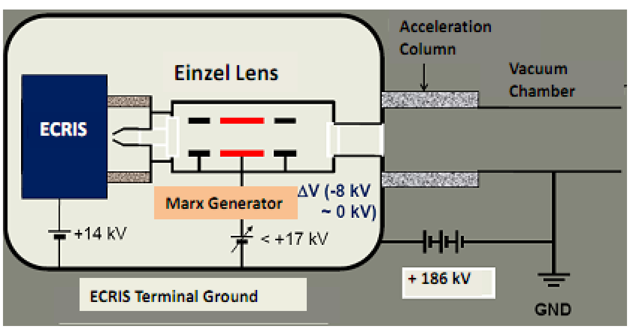

Figure 2: Schematic of the High Voltage Trerminal and its contents

LONGITUDINAL CHOPPER

Barrier Voltage Blocking

The IGUN [5] program was used to simulate the beam orbits from the cathode hole to the anode and from the anode through the Einzel lens as shown in Fig.3.. A case where the middle electrode voltage V_1 is increased to 15 kV is shown there. It can be seen that reflection from the region is not sufficient. At V_1=17 kV, all the ions are reflected upstream and never propagate downstream. Both the IGUN simulations and the experimental results show that somewhat higher voltage than V_0 is required for perfect repelling of ions dispatched from the ECRIS with an energy of QeV_0, where Q is the charge state of the ions. This is understandable from the fact that the potential is V_0 only at the surface of the middle electrode of the Einzel lens, and the potential on the beam axis is always less than that at the surface. The potential on the beam axis is uniquely determined by the geometry of the Einzel lens and the potential of the electrodes.

In order to confirm ion beam blocking by the barrier voltage, the beam current passing through the Einzel lens was measured as a function of V_1. The result was consistent with the IGUN simulation, as shown in Fig. 4.

Solid-state Marx Generator

Marx generators are well known in pulse power technology. In Marx generator, a DC power supply

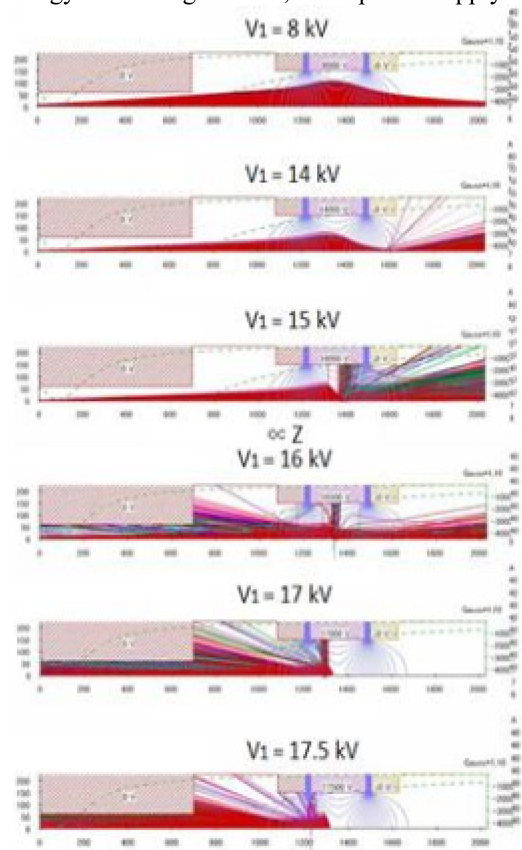

Figure 3: Simulated tracks of ions from the cathode to the anode and from the anode through the Einzel lens, where V_0 = 14 kV and V_1 = 8 - 17.5 kV

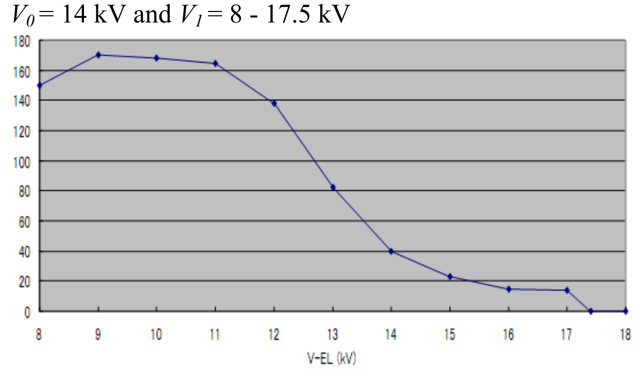

Figure 4: Beam current passing through the Einzel lens as observed with a Faraday cup downstream vs. the Einzel lens electrode voltage V_1

providing relatively low voltage feeds multiple capacitors connected in parallel, and elements are switched rapidly to close the Marx circuit, shown in Fig. 5 for the present system, and connect the capacitors in series. As a result, individual voltages shared by the capacitors sum up to generate a high-voltage pulse. The pulse duration is uniquely determined by the on-time period of the switches. When a switching element is a solid-state device such as a MOSFET, it is possible to obtain a rectangular pulse with a rise/fall time of 10-20 ns. Our Marx generator consists of 4 capacitors, which are fed with a 2 kV DC power supply and connected with adjacent capacitors by turning on MOSFET switches [6]. SPICE simulations were carried out in order to optimize the circuit parameters of this Marx generator. Fig.5 shows the actually obtained super imposed voltage of the middle electrode.

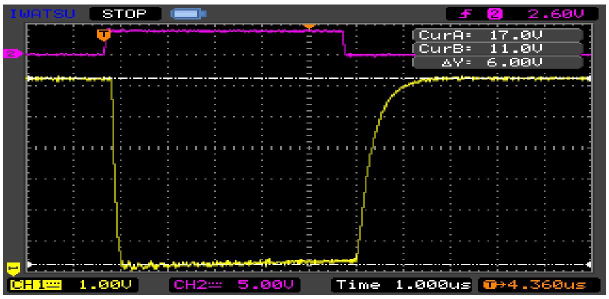

Figure 5: Voltage of The Einzel lens middle electrode

EXPERIMENTAL RESULTS

The operational performance of our Einzel lens chopper driven by a Marx generator was preliminarily confirmed at the ECRIS test bench, where an ion beam was extracted with the extraction voltage V_0 from the ECRIS. The beam was chopped and guided to the diagnostics region where the Faraday cup was installed. Then, the ECRIS with the chopper were set up inside the HVT and the entire system was installed in the low-energy beam transportation line (LEBT) shown in Fig. 1. The upstream part of the LEBT, including the 45-degree bending magnet BM2, served as a practical setup for the Einzel lens chopping beam experiment, where the straight beam line immediately after the B2 was equipped with the beam diagnostics system including the Faraday cup and a screen monitor. The FET switches for the Marx generator were turned on based on the trigger signal for the pulse mode operation of the TWT at 10 Hz. The beam current was monitored with the Faraday cup with an electron-shielding electrode. The monitoring circuit consisted of a stray capacitance of 47 pF, a metal coating resistor of 1 kΩ, and an oscilloscope connected with a coaxial cable.

In the experiment, the extraction voltage from the ECRIS and the static Einzel lens voltage to secure complete blockage of the beam propagation were fixed at 14 kV and 17 kV, respectively. Since the Einzel lens voltage for beam optics matching through the downstream was already optimized to be 11 kV, a pulse voltage of -6 kV and 5 μs, which was generated by the Marx generator, was superimposed onto the DC bias voltage of 17 kV at the middle electrode of the Einzel lens. The ion current of He^{1+} was monitored with the FC. A typical non-chopped He^{1+} pulse of 5 ms is shown in Fig. 6. Current profiles of the chopped beam in Fig. 7 were obtained at different times during the 5 ms pulse. The rise/fall times in the pulse profiles can be explained by the parameters of the FC monitoring circuit, that is, a time constant $\tau = RC$ which is uniquely determined by the resistance and the stray capacitance:

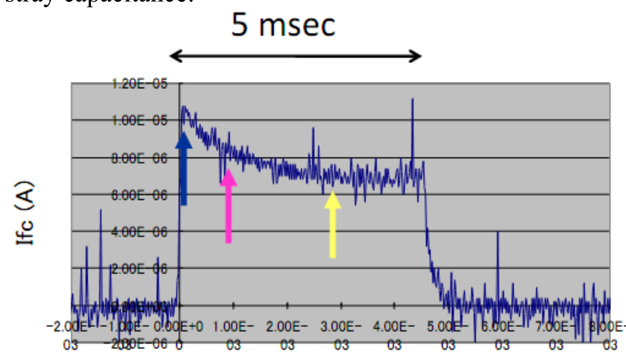

Figure 6: 5 ms ion beam pulse monitored with the Faraday cup

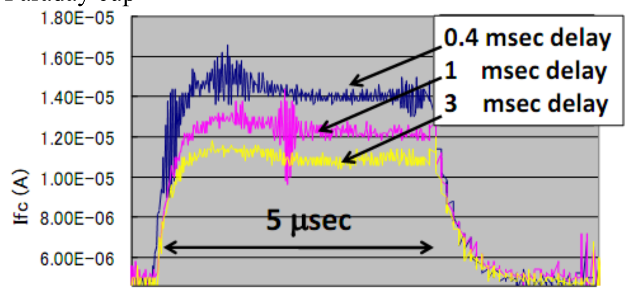

Figure 7: 5 μs chopped pulse profiles, which are chopped at different times from the pulse head of a 5 ms ion pulse

SUMMARY

We have successfully demonstrated the operation of an Einzel lens chopper driven by a solid-state Marx generator. A He^{1+} ion beam delivered from an ECRIS was chopped to the desired pulse length by controlling the Einzel lens electrode voltage in time. A solid-state Marx generator which can achieve sharp voltage pulses with short rise/fall times, was developed. The chopper is continuously being used for beam commissioning of the KEK-DA [7]

REFERENCES

[1] T.Adachi, T.Arai, K.W.Leo, K.Takayama, and A.Tokuchi, *Rev. Sci. Inst.* **82**, 083305 (2011).
[2] T. Iwashita *et al.*, *Phys. Rev. ST-AB 14,* 071301 (2011)
[3] K. Takayama *et al.*, *Phys. Rev. Lett.* **98**, 054801-4 (2007).
[4] "Induction Accelerators", K.Takayama and R.Briggs (*Eds.*) (Springer, 2010).
[5] Leo Kwee Wah *et al.*, *19th Int. Workshop on ECRIS*, August 23-26, 2010 Grenoble, France, TUPOT15 (2010).
[6]W.Jiang introduced an solid-state Marx generator to us.
[7] K.Takayama *et al.*, in this conference WEOBA02.