Beam Dynamics Analysis of Heavy Ion Injection into the KEK Digital Accelerator

Hiroshi KOBAYASHI[1,2], Xinggung LIU[2,3], Takashi YOSHIMOTO[2,3], Ken TAKAYAMA[1,2,3], Tadamichi KAWAKUBO[2] and Toshikazu ADACHI[2,4]

[1]*Tokyo City University, Setagaya, Tokyo 158-8557, Japan*
[2]*High Energy Accelerator Research Organization/Accelerator Laboratory (KEK), Tsukuba 305-0801, Japan*
[3]*Tokyo Institute of Technology, Nagatsuda, Midori-ku, Yokohama 226-8503, Japan*
[4]*The Graduate University for Advanced Studies (SOKENDAI), Hayama, Kanagawa 240-0193, Japan*

(Received 14 January 2016 / Accepted 27 March 2016)

An electrostatic kicker is used for heavy ion beam injection into the KEK digital accelerator (DA) ring. A voltage of 20 kV, which must be immediately turned off after injection, is applied across the electrostatic electrodes before injection so as to deflect the injected beam into the ring orbit. An SI-Thyristor Matrix Array (SI-Thy MA) has been developed to replace the conventional thyratron switching device. Long ringing in the turn-off voltage affects the longitudinal motion of the injected beam bunch, resulting in the formation of microstructure. The physics behind the microstructure formation is discussed in detail.

Keywords: KEK-DA, SI-Thyristor Matrix Array, longitudinal beam dynamics, space charge effect, microstructure

DOI: 10.1585/pfr.11.1404092

1. Introduction

The KEK-DA [1], which has been developed from the former KEK 500MeV Booster synchrotron, is a small scale induction synchrotron capable of accelerating all ion species from H to Au. Instead of an RF cavity, induction acceleration devices are employed for acceleration and beam confinement. Various applications for heavy ions delivered from the KEK-DA are expected [2]. Figure 1 shows a schematic view of the KEK-DA.

Thyratron is a quite old invention [3]. It has long taken a unique and indispensable role in pulse power technology as a high power and fast switching device. Its drawbacks such as hard-work associated with its replacement, rigorous condition for its stock, and short life-time, however, have been frequently pointed out. Realization of the solid-state matrix array capable of replacing the thyratron is expected to eliminate all of these issues. This replacement is crucial for future accelerators, especially gigantic quantum beam inertial fusion drivers [4], where a lot of pulsed power devices such as injection/extraction kickers and induction acceleration devices are assumed to be employed [5].

Recently, SI-Thyristor Matrix Array (SI-Thy MA) [6] has been developed to replace the conventional Thyratron switching device in KEK-DA. It has been seen that ringing (of 3.5 μs duration) in a voltage pulse affects beam injection dynamics, resulting in micro bunch formation. ES-Kicker voltage waveforms for both switches are shown in Fig. 2, in which the difference in switching speed between both devices can be seen. Fortunately, this problem was overcome by optimizing the discharging time. When a long bunch, called a super bunch [2, 7], is injected, however, this ringing could become significant and limit the acceptable beam length. It is, therefore, important to in-

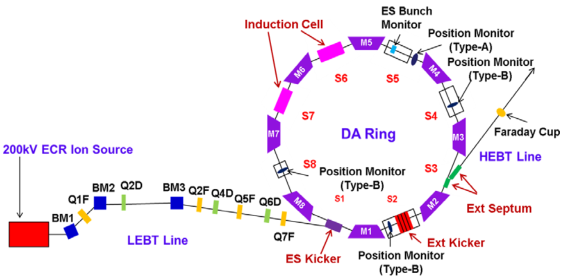

Fig. 1 Schematic view of the KEK-DA.

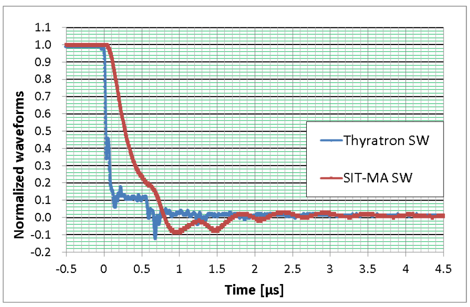

Fig. 2 ES-kicker voltage waveforms for both switches.

author's e-mail: khiroshi@post.kek.jp

vestigate how this influences the injected beam in the time domain. A computer simulation that takes longitudinal space-charge effects into account has been developed in order to fully understand what happens.

This paper describes experimental results from the free-run mode with no acceleration or confinement and its analysis via macro-particle simulation.

2. Experimental Setup

2.1 Injection kicker

The ES-kicker acts on the injected beam through an electric field. The ES-kicker is installed in the vacuum duct, as shown in Fig. 3, and consists of a high-voltage electrode, ~~a~~ ground electrode, and three intermediate electrodes. The beam is kicked horizontally into the ring orbit when a high voltage of about 20 kV is applied across the electrodes. To obtain the desired field homogeneity, the voltage is equally divided between the intermediate electrodes by resistors.

Figure 4 shows the ES-kicker driver circuit system. The high-voltage electrodes and resonant power supply are connected by a coaxial cable. This coaxial cable works as a pulse-forming network and is charged to the required voltage by the resonant charging power supply.

Before the injected beam completes the first turn and enters the ES-kicker, the kicker field must be turned off; otherwise, the beam is deflected horizontally. For this purpose, the switching device is turned on for discharging. Charges flow to ground through the matching resistor and the voltage across the electrodes disappears. The voltage on the high-voltage electrode is expected to vary with time.

2.2 SI-Thy MA switch

The SI-thyristor (N403) was manufactured by Shindengen Electric Company. It has the following specifications: voltage resistivity of 4 kV and maximum peak current of 300 A. The SI-Thy MA consists of 10 SI thyristors in series that have a total withstand voltage of over 20 kV. The present SI-Thy MA was assembled by Pulsed Power Japan Laboratory Ltd. The assembled unit is shown in Fig. 5. The thyristors on each circuit board are simultaneously turned on by a gate signal sent through optical fibers which are connected to the external gate module implemented in the KEK-DA operating system.

Voltage ringing continues for about 3.5 μs after turning on the SI-Thy MA, which is longer than that of the thyratron. Fortunately, the ringing does not cause any actual problem, even in the case of a short hydrogen ion beam with $A/Q = 1$ (A: Mass number; Q: charge state), for which the revolution time is 6 μs, much longer than the ringing duration. It is also tolerable in nominal operation where the beam pulse length is limited to 4 μs. The ringing in voltage oscillates in time with damping. The observed oscillation period was about 550 ns.

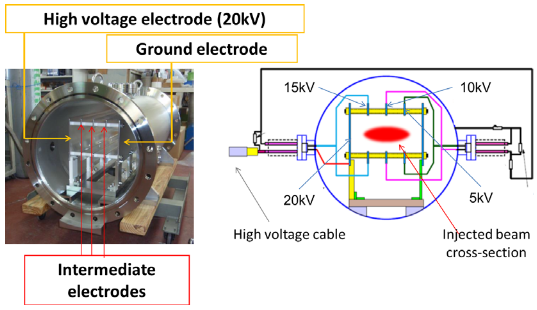

Fig. 3 ES-kicker in the vacuum chamber (photo) and schematics of its electric wiring.

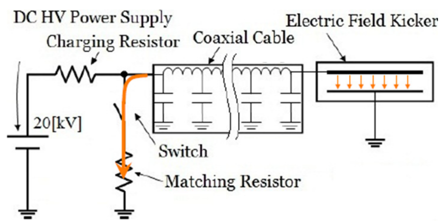

Fig. 4 The ES-kicker excitation circuit.

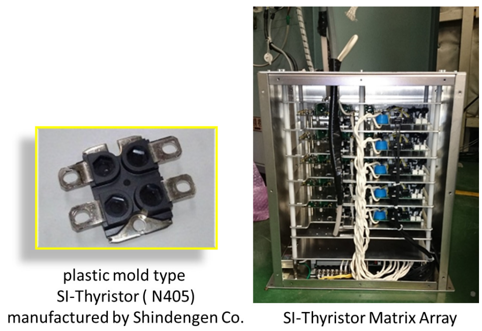

Fig. 5 SI-Thy package and SI-Thyristor MA.

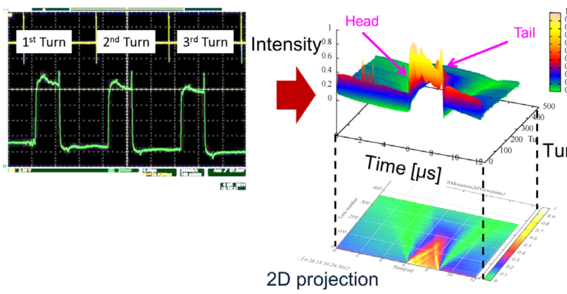

Fig. 6 The raw beam signal observed by the electrostatic bunch monitor and its mountain plot.

2.3 Bunch monitor system

A mountain plot of the line density was generated from the beam signal observed by the electrostatic bunch monitor, and is shown in Fig. 6. Its projection onto the x-y

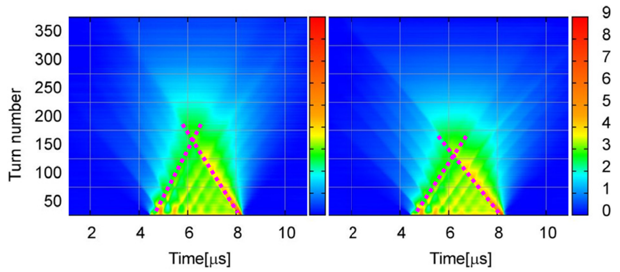

Fig. 7 Temporal evolution of the injected bunch for 35 μA (left) and 70 μA (right).

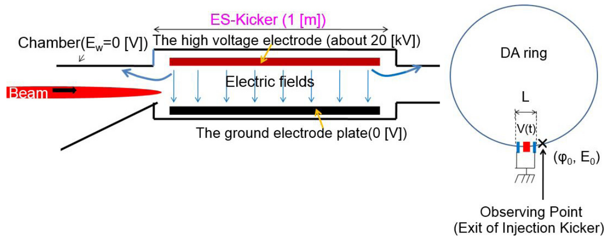

Fig. 8 The model of the ES-kicker with the residual electric fields and the accelerator ring model with the observation point located at the exit of the ES kicker.

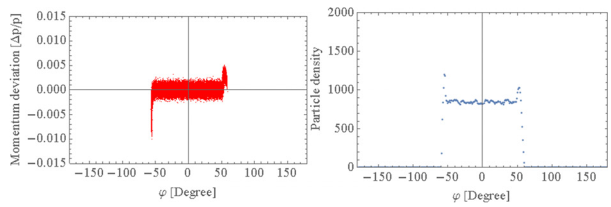

Fig. 9 Phase plot and line density of macro-particles for a beam current of 35 μA at injection.

plane is shown at the bottom of Fig. 6.

3. Experimental Results

Since early in the operation of the DA ring, interesting phenomena related to this voltage ringing have been reported. The creation and annihilation of micro bunches, as seen in Fig. 7, are among them. To investigate such ringing effects from the beam dynamics point of view, extensive injection experiments have been conducted. Experiments adjusting the kicker discharge timing have clearly suggested that the ringing is directly responsible for perturbations of the circulating beam bunch. It has been discovered that residual electric fields generated at the entrance and exit of the ES-kicker, originating from the ringing voltage, affect the longitudinal beam dynamics. In addition, it has been observed that the creation of microstructure strongly depends on beam intensity. Figure 7 shows the temporal evolution of the injected bunch for two different beam currents. The injected bunches circulated without any confinement in the longitudinal direction.

Immediate micro-bunch formation just after injection with drift to both sides and disappearance are clearly visible in Fig. 7. There is an apparent difference in the drift speed toward both sides for the two beam currents. The cross point of the bunch head and tail is known to be around 120 and 100 turns for beam currents of 35 μA and 70 μA, respectively. In addition, the microstructure's drift speed is different for the two cases. There is a maximum momentum deviation of 0.1% for 35 μA and 0.2% for 70 μA.

4. Analytical Model

In order to understand how the injected particles behave under the residual fields, an original macro-particle simulation has been developed. The physics model that explains the ringing effect is shown in Fig. 8. The ES-kicker region is 1 m long, and the transit time (τ) necessary for a particle to pass the kicker region is about 330 ns. It is clear that the net effect of the residual voltage remains in the energy gain of a particle passing through the injection kicker. The electric fields exist at both edges of the ES-kicker electrodes because the surrounding vacuum chamber is always grounded. This field should accelerate or decelerate particles in the longitudinal direction at the second turn. We assume the observation point shown in Fig. 3, where the motion of particle is monitored in terms of phase ϕ and energy E.

5. Numerical Simulations

An initial distribution of 10^5 macro-particles is assumed so as to mimic the actual situation, shown in Fig. 9, where the beam core's maximum momentum deviation $(\Delta p/p)_{\max}$ is 0.2% and its width in phase is 120 degrees, corresponding to a 4-μs injected beam bunch. The values of $(\Delta p/p)_{\max}$ in the head and tail have been determined from other experimental results [8, 9].

The residual voltage V is assumed to follow a damped sine function. The energy gained by macro-particles is

$$\Delta E = Qe\,[V(t+\tau) - V(t)]\,, \tag{1}$$

where τ is the transit time and Q is the charge state of the ion. At 1 turn after injection, the particle distribution changes, as shown in Fig. 10, and there is a large modulation in the momentum direction; however, the line density is almost same as that shown in Fig. 9. In the case with no external forces, the macro-particle distribution evolves following a step equation for the phase, keeping the same $\Delta p/p$:

$$\phi_{n+1} = \left\{\phi_n + 2\pi\eta \cdot \frac{\Delta p}{p}\right\} \quad (\eta < 0)\,. \tag{2}$$

Here, n is the turn number and η is the phase slippage factor. The simulation result is shown in Fig. 11. The creation,

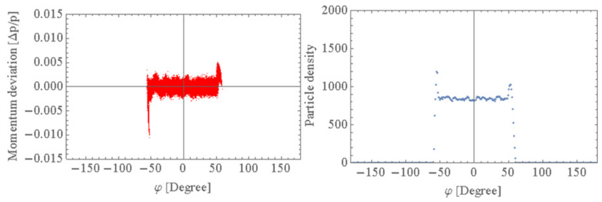

Fig. 10 Phase plot and line density of the macro-particles just after passing the ES-kicker region for a beam current of 35 µA.

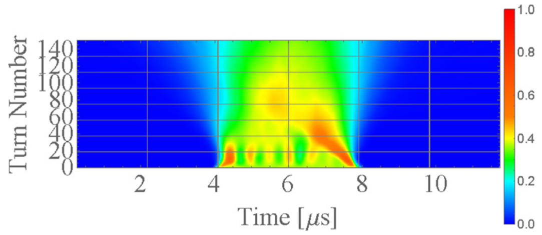

Fig. 11 Projection of the line density onto the time axis.

drift, and annihilation of the microstructure in the bunch can be clearly seen.

The microstructure formation is reproduced in the simulation. Thus, the modulation in the momentum due to the residual voltage seems to cause microstructure formation. However, the drift speed in the 2D time space obtained from the simulations seems to be different from the experimental result. The observed drift speed gives the following maximum deviations of momentum of the beam core.

$$\left|\left(\frac{\Delta p}{p}\right)\right|_{\max} = \begin{cases} 0.13\% \text{ for } 35\ [\mu\text{A}] \\ 0.26\% \text{ for } 70\ [\mu\text{A}] \end{cases}.$$

This difference is apparently due to the difference in the beam current.

Longitudinal space charge effects may be a possible candidate that can explain this difference. The longitudinal space charge effect can be written as

$$E_S = -\frac{g_0}{4\pi\varepsilon_0\gamma^2} \cdot \frac{\mathrm{d}\lambda}{\mathrm{d}s}, \tag{3}$$

where g_0 is a geometric factor determined from the vacuum chamber and averaged beam size, ε_0 is the dielectric constant of the vacuum, γ is the relativistic gamma of an ideal particle, and λ is the line density.

It is customary to include the space charge effects as a delta function-like kick in the beam-tracking simulation, under the assumption that the change in phase per turn for a particle is quite small, as shown in the following step equation:

$$E_{n+1} = E_n + Qe(C_0 \cdot E_S + V_{\mathrm{int}}). \tag{4}$$

Here, C_0 is the orbit circumference (37.7 m).

Table 1 Beam parameters at injection.

Beam Current	35 or 70 µA
Beam length	4 µs
A/Q	4
v/c	0.01

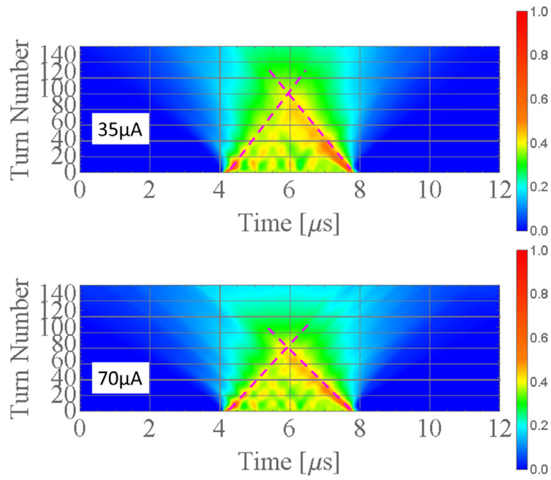

Fig. 12 Temporal evolution of the injected bunch for beam currents of 35 µA (upper) and 70 µA (lower).

6. Discussion

Table 1 shows the beam parameters in the experiments and numerical simulations.

Simulation results taking account of the space charge effects are shown in Fig. 12. It can be seen that the crossing of the beam head and tail occurs around 100 turns for 35 µA and 80 turns for 70 µA. Thus, the difference in the crossing point mentioned in the previous subsection has been confirmed.

The maximum momentum deviation of the microstructure obtained from the simulation results is 0.15% for 35 µA, and 0.21% for 70 µA. These magnitudes are very close to the momentum deviations mentioned in the previous subsection.

7. Conclusion

We can conclude that beam dynamics at injection in the KEK-DA cannot be explained without including longitudinal space charge effects. The residual ringing voltage accompanying the turning on of a solid-state switch may determine the maximum beam length in an all future solid-state ring accelerators.

[1] T. Iwashita *et al.*, Phys. Rev. ST-AB **14**, 071301 (2011).
[2] K. Takayama *et al.*, Nucl. Instrum. Methods B**314**, 11 (2013).
[3] A.W. Hull, Trans. AIEE **47**, 753 (1928).
[4] K. Takayama *et al.*, Plasma Fusion Res. **89**, 87 (2013).

[5] T. Adachi and T. Kawakubo, Phys. Rev. ST-AB **16**, 053501 (2013).
[6] H. Kobayashi, T. Kawakubo and A. Tokuchi, Proceedings of 5th Euro-Asian Pulsed Power Conference, September 8-12, 2014, Kumamoto, Japan, 23-26.
[7] K. Takayama, *Induction Accelerators* (Springer, Berlin/New York, 2011) Chapter 12.
[8] Leo Kwee Wah *et al*., Phys. Rev. ST-AB **16**, 043502 (2013).
[9] Liu Xigguang *et al.*, submitted to Nucl. Instrum. Methods A (2015).