SI-THYRISTOR MATRIX ARRAY DRIVEN ELECTROSTATIC INJECTION KICKER FOR THE KEK DIGITAL ACCELERATOR AND BEAM DYNAMICS ANALYSIS OF INJECTION

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Abstract

The electrostatic (ES) kicker is used for heavy ion beam injection [1] into the KEK digital accelerator (DA) ring [2]. A voltage of 20 kV, which must be immediately turned off after injection, is put across the electrostatic electrodes before injection so as to deflect the injected beam on the ring orbit. The SI-Thyristor Matrix Array (SI-Thy MA) as a turning off switching device has been developed to replace the conventional thyratron [3]. The long ringing in the turn-off voltage affects on longitudinal motions of the injected beam bunch. Its careful analysis is discussed here.

INTRODUCTION

Voltage ringing continues for about 3.5 μs after switching on of the SI-Thy MA as shown in Fig. 1. It is apparently longer than that of the thyratron. This is caused by intrinsic natures of the SI-Thy MA. Details of the newly developed SI-Thy MA were reported in Reference 3. Fortunately, such relatively longer ringing time duration does not become any actual problem even in the case of hydrogen ion of *A/Q*=1, because its revolution time of 6 μs is much longer than the ringing time duration . The ringing in voltage vibrates in time with damping. The oscillation period is about 550 ns.

Since its operation we have noticed interesting phenomena related to this voltage ringing. Creation and annihilation of micro-bunches as seen in Fig. 2 are among them. In order to investigate such ringing effects on the beam dynamics, extensive injection experiments were conducted. From the experiment adjusting the kicker discharge timing, the ringing was known to be responsible for perturbations on the circulating beam bunch. As a result, it turned out that the residual electric fields generated at an entrance and the exit of the ES-kicker, originating from the ringing voltage affects on the longitudinal beam dynamics. In addition, it has been observed that the creation of microstructure strongly depends on a beam intensity.

The physics model that explains the direct ringing effect is shown in Fig. 3. The ES-kicker region is 1 m long, and the transit time (τ) necessary for a particle to pass the region is about 330 ns. It is clear that the net effect of the residual voltage remains in the energy gain of a particle during passing the injection kicker.

For the purpose to fully understand the longitudinal beam dynamics in the early stage just after injection, the simulation program has been developed, which takes account of the longitudinal space charge effect and wake fields in an isolated impedance with the oscillation frequency close to the microstructure. The observation point is shown in Fig. 3. φ and E in the Figure denote the phase and the energy of the macro-particles at the observed point.

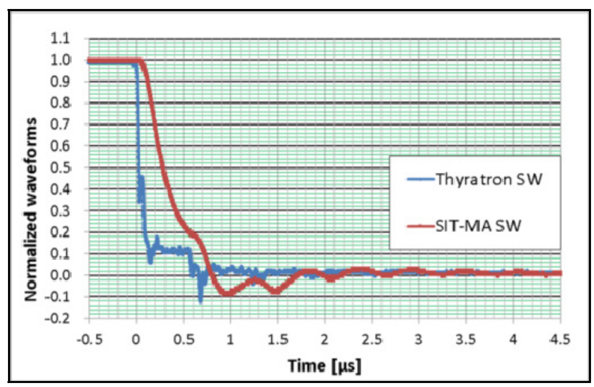

Figure 1: ES-Kicker voltage waveforms for both switches.

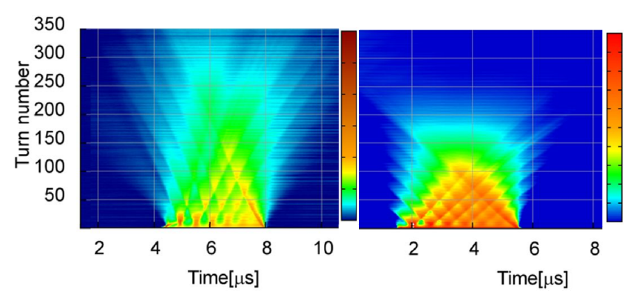

Figure 2: Temporal evolution of the injected bunch for 40 μA (experiment: left) and 100 μA (experiment: right), the line density is projected on the 2D time space, the time within a single revolution (the horizontal direction) and time from the injection (the vertical direction).

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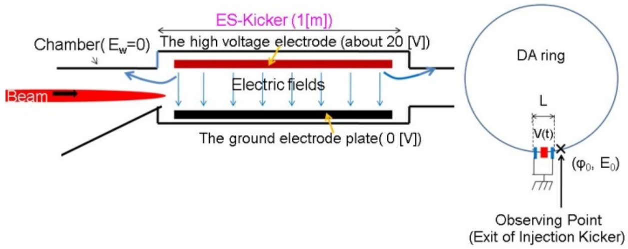

Figure 3: Analytical model for the injection kicker and Analytic model for interaction, where the dynamical parameters (φ, E) of macro-particles are picked up at the observing point.

NUMERICAL SIMULATION

The initial condition for the distribution of the macro-particles of 10^4 is assumed so as to mimics the actual situation as shown in Fig. 4, where the maximum momentum deviation $(\Delta p/p)_{\max}$ is 0.2 % and its width in phase is 120 degrees corresponding to the injected beam bunch of 4 μs.

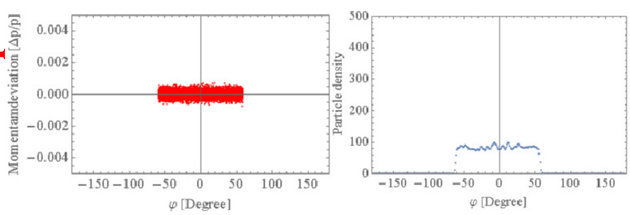

Figure 4: Phase plot and line density of macro-particles at injection timing.

Residual voltage V is assumed by a dumped Sin function. The energy gain by macro-particles is written by

$$\Delta E = Qe\left[V(t+\tau) - V(t)\right] \qquad (1)$$

where τ is transit time and Q is the charge state of ion. At 1 turn after injection, thus, the particle distribution changes as shown in Fig. 5, where there is a large modulation in the momentum direction, meanwhile, the line density is almost same as in Fig. 4. In the situation that any external forces do not act on, the macro particles distribution evolves following the step equation for the phase keeping the same $\Delta p/p$,

$$\varphi_{n+1} = \left\{\varphi_n + 2\pi\eta\cdot\frac{\Delta p}{p}\right\} \quad (\eta < 0) \qquad (2)$$

where n is the turn number. The simulation result is shown in Fig. 6. Creation and its drift and annihilation of the micro structure in the bunch are clear.

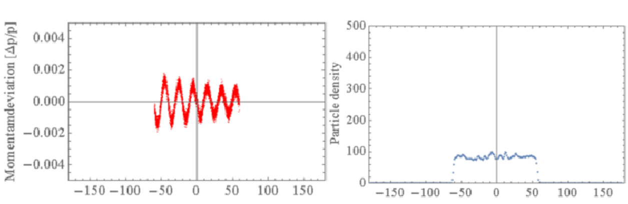

Figure 5: Phase plot and line density of the macro-particles just after passing the ES-kicker region.

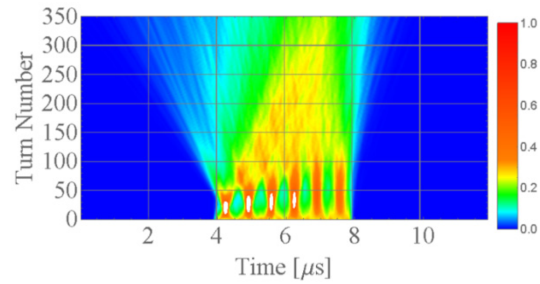

Figure 6: Projection of the line density on time axes (revolution time and turn number) for 100 μA.

The microstructure formation is reproduced. It turns out that the modulation in the momentum due to the residual voltage is a source causing the micorstructure. However, the drift speed on the 2D time space seems to be different from the experimental result. From the observed drift speed, the maximum momentum deviation is evaluated as follows,

$$\left|\left(\frac{\Delta p}{p}\right)\right|_{\max} = \begin{cases} 0.1\ \%\ \text{for}\ \ 40\ \ [\mu\text{A}] \\ 0.2\ \%\ \text{for}\ 100\ [\mu\text{A}] \end{cases}$$

This difference is apparently attributed to the discrepancy in the beam current.

The longitudinal space charge effects and wake fields effects may be possible candidates that can explain this difference. The longitudinal space charge effects and wake fields effects are known to be written by the following equations.

$$E_S = -\frac{g_0}{4\pi\varepsilon_0\gamma^2}\cdot\frac{d\lambda}{ds} \qquad (3)$$

where g_0 is the average geometric coefficient of the vacuum chamber, ε_0 is the dielectric constant of vacuum, γ is the relativistic gamma (approximately one), λ is a line density,

$$V_{\text{int}} = \frac{\omega_{rf}}{TTF}\left(\frac{R_{shunt}}{Q}\right)\int_{\varphi_{head}}^{\varphi} \exp\left(-\frac{\omega_\lambda(\varphi-\varphi')}{2Q\omega_{rf}}\right)\times\sin\left(\frac{\omega'_\lambda}{\omega_{rf}}(\varphi'-\varphi)\right)\frac{\partial\lambda(\varphi')}{\partial\varphi'}d\varphi' \qquad (4)$$

[4] where ω_{rf} is the revolution frequency, TTF is the transit-time factor of the resonant impedance structure (assumed 1 for simplicity), R_{shunt} is the shunt impedance, Q is quality factor (~10). ω_λ is ringing frequency and $\omega'_\lambda \approx \omega_\lambda$.

It is a custom to include the space charge effects and wake fields effects as a delta function-like kick in the beam tracking simulation, under an assumption that the member change in phase by 1 turn is small, as shown in the following step equation,

$$E_{n+1} = E_n + Qe(C_0\cdot E_S + V_{\text{int}}) \qquad (5)$$

where C_0 is the orbit circumference (37.7 m).

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SIMULATION RESULTS WITH OTHER EFFCTS

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

Table 1: Beam Parameters at Injection

Beam Current	40,100 μA
Beam length	4 μs
A/Q	4
v/c	0.01

Simulation results with the space charge effects are shown in Fig. 7 and 8.

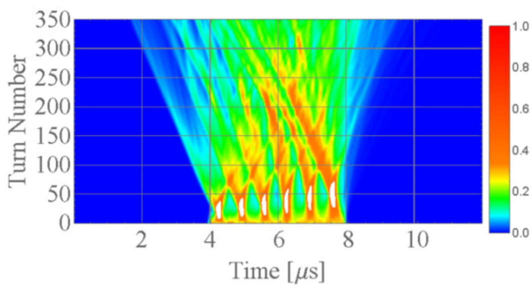

Figure 7: Temporal evolution of the injected bunch for 40 μA.

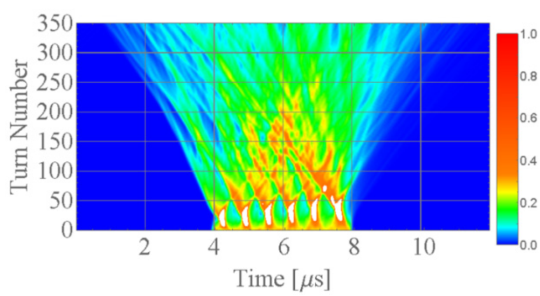

Figure 8: Temporal evolution of the injected bunch for 100 μA.

The diffusion speed seems to be still lower than the experimental results for both cases of 40 μA and 100 μA. This fact tells us that the space-charge effects are not enough to quantitatively explain increasing of the momentum deviation to result in the diffusion on the 2D time space. At last we arrive at wake field effects. Honestly speaking, we have no information about the impedance of the beam pipe, especially in the range of MHz. Unknown parameters except the resonance frequency ω_λ, such as the Quality factor Q and shunt impedance R_{shunt}, are assumed to be free-parameters in the simulation. Simulation results taking account of both of the space charge effects and wake fields effects are shown in Fig. 9 and 10, where Q=5 and R_{shunt}=1 Ω are assume .

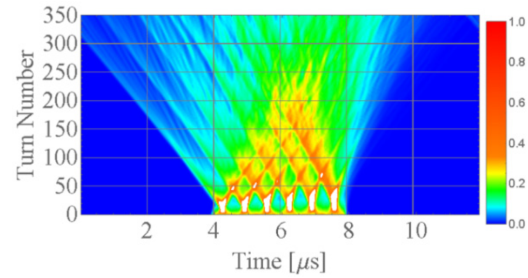

Figure 9: Temporal evolution of the injected bunch for 40 μA (simulation with space-charge effects and wake fields effects).

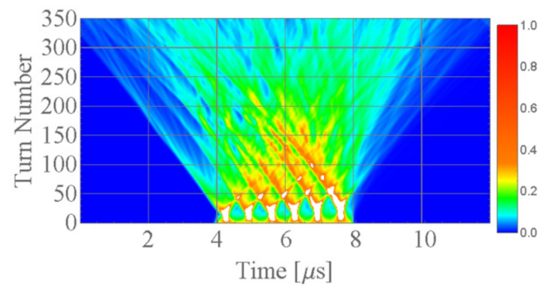

Figure 10: Temporal evolution of the injected bunch for 100 μA.

The simulation results seem to be in good agreement with the experimental result.

CONCLUSION

The influence of the longitudinal space charge effect was evaluated during the circulation of the low energy ion beam in the KEK-DA. The numerical simulation has suggested that the experimental results are not explained without the effects of wake fields. The topics is rather academic; the replacement of the Thyratron by the SI-Thy MA happened to give a good chance to study the microstructure created in the beam bunch that is visible in the distinct way.

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