# Bunch Rotation using Sawtooth RF

Ryosaku MURAMATSU†, Miho FUJIEDA‡, Yoshiharu MORI, Chihiro OHMORI,
Yasuo SATO§, Masanobu YAMAMOTO¶, Mitsutaka KANAZAWA*, Koji NODA*
KEK-Tanshi, 3-2-1 Midori-cho, Tanashi 188–8501, Japan
*NIRS, Chiba 263–8555, Japan

**Abstract**

Bunch rotation is useful scheme to obtain a short bunch from a long bunch with a small momentum spread. On the contrary, it is also applicable to lengthen the beam from a short bunch. In order to rotate a bunch, a sawtooth RF is more effective than a sine-wave due to its linearity. A sawtooth wave was generated using an MA (Magnetic Alloy) cavity which was installed at the HIMAC and was applied for the bunch rotation. It was found that it could minimize the filamentation caused by a non-linearity of RF voltage.

## 1 Introduction

A high-energy physics experiment requires a short bunch of a few 10 ns width in the synchrotron. A chemical experiment also requires it to measure a free-radical in the materials. On the other hand, it is necessary to form a long beam bunch with a narrow momentum spread from very shortly-bunched secondary muon beam for another high-energy physics experiments.

A bunch rotation[1] in the longitudinal phase space is a scheme to satisfy their requirements. So far, a sine-wave has been applied to rotate the beam bunch in the longitudinal phase space. However, the angular velocities of particles depend on the amplitude of the oscillation in the phase space. A particle with a small amplitude rotates faster than that with a large one. Because of the difference of the angular velocity, a filamentation occurs in the phase space, which causes that the particles near the edge form the tail as shown in Fig. 1(a) when the bunch is sharpened.

On the other hand, a sawtooth wave is suitable for the rotation because all particles have a same angular velocity and the filamentation is minimized (Fig. 1(b)). However, it was very difficult to apply the sawtooth wave because it includes many RF frequencies. Many RF cavities have been necessary so as to generate it. An MA (Magnetic Alloy) cavity[2, 3, 4] is suitable for the sawtooth RF because it has a broadband impedance. It can generate the different RF frequencies simultaneously at an acceleration gap and enable to obtain the sawtooth wave by a single cavity.

## 2 Experiments

A bunch rotation experiment was performed at the HIMAC synchrotron. An MA cavity was installed for the beam test[5, 6]. The cavity was driven by a power amplifier using two 30 kW tetrodes, 4CW 30,000A. The maximum voltage of 5 kV was obtained.

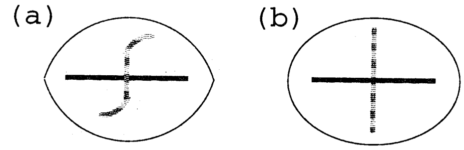


Fig. 1 Bunch rotation in the longitudinal phase space by (a) sinusoidal wave and (b) sawtooth rf, respectively.

### 2.1 Sawtooth RF

Ideal sawtooth rf can be obtained by Fourier series;

$$V(\varphi) = \frac{2V_{peak}}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{n} \sin n\varphi$$

Three harmonic frequencies were combined to generate a pseudo-sawtooth wave and their relative phases and amplitudes were optimized. The fundamental frequency (h=4, 1.046MHz) was generated by a synthesizer (HP 3326A). The second harmonic frequency (h=8, 2.092MHz) was created by a frequency doubler from the fundamental frequency. They were mixed by a mixer and the third harmonic frequency (h=12, 3.138MHz) was generated. Although both MA cavity and power amplifier are broadband system, their frequency responses for each harmonics are different. Therefore the waveform at the driver amplifier was not the sawtooth-like. Figure 2 shows the waveform at the acceleration gap of the cavity. The gap voltage was measured by a voltage divider.

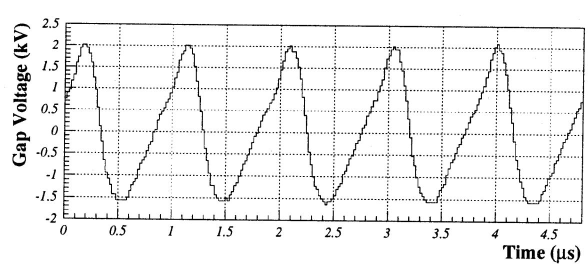


Fig. 2 Waveform at the acceleration gap of the cavity.

### 2.2 Experimental scheme

First of all, the coasting beam was bunched by the barrier RF voltage[7]. If the coasting beam is rotated directly, the filamentation occurs and it causes that the

†also: University of Tokyo
‡also: Kyoto University
§also: Japan Steel Works Co. Ltd.
¶also: RCNP, Osaka University

difference between sawtooth RF and sine-wave is not very clear. Then the bunch was rotated by the sawtooth wave.

The maximum momentum spread of the beam is limited up to ± 0.3 % due to the longitudinal acceptance of the HIMAC. However, the momentum spread of the linac beam is about ± 0.1 %. Therefore, it is difficult to obtain the very short bunch by the bunch rotation. To study the bunch rotation scheme more carefully, a bunch was rotated for several times and the damping of quadrupole oscillation was measured. The beam bunch was measured by a position monitor in the synchrotron. For the comparison, the bunch rotation by the sinusoidal wave was also performed. The peak voltage of the sawtooth RF was 2kV. The frequency was 1.046MHz, which corresponded to the harmonics h=4.

### 2.3 Experimental result

The mountain range plots of the beam bunch shape are shown in Fig. 3. The period between each line is 20 $\mu$s. Figure 4 shows the envelope of the beam bunch signals.

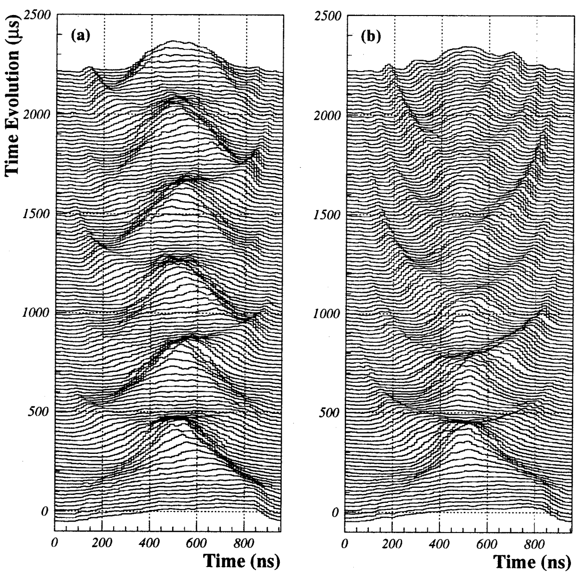


Fig. 3 Mountain range plots of the beam bunch for (a) the sawtooth RF and (b) sine-wave. The period between each line is 20 $\mu$s.

One can see clearly that the bunch was rotating in Fig. 3. In the case of sine-wave, the quadrupole oscillation was damped quickly as shown in Fig. 3(b) and Fig. 4(b). On the other hand, it continued longer in the case of the sawtooth RF as shown in Fig. 3(a) and Fig. 4(a), because of the linearity of the sawtooth voltage. Therefore this experiment suggests that the sawtooth RF is more suitable for the bunch rotation than the sine-wave. The minimum bunch width for both waves was about 250 ns there, which was consistent with the initial momentum spread. If the momentum spread of the beam is narrow, a shorter bunch will be achieved.

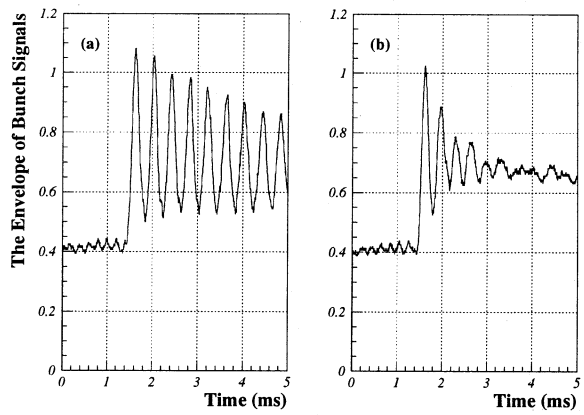


Fig. 4 Envelope of the beam bunch signal for (a) sawtooth RF and (b) sine-wave. Fig. 4 (b) shows that the quadrupole oscillation is damped in a few turns because of the nonlinearity of the RF bucket.

## 3 Conclusion

A bunch rotation experiment was performed at the HIMAC synchrotron. A beam bunch was rotated by both sawtooth and sinusoidal RF. The quadrupole oscillation survived for long period in the linear bucket produced by the sawtooth wave. It was found that the sawtooth RF was more effective for the bunch rotation than the sine-wave due to its linearity.

## Acknowledgments

We would like to thank the NIRS staffs and AEC people for machine tuning and stable operation. We would like to be grateful to Tom. Uesugi for his fruitful advices.

## References

[1] P. S. Martin et al., "Bunch Coalescing and Bunch Rotation in the Fermilab", Proc. of EPAC, 1988
[2] C. Ohmori et al., "A Wideband RF Cavity for JHF Synchrotrons", Proc. of 1997 PAC, 1997.
[3] Y. Mori et al., "A New Type of RF Cavity for High Intensity Proton Synchrotron using High Permieability Magnetic Alloy", Proc. of the 6th EPAC, 1998.
[4] C. Ohmori et al., "High Field-Gradient Cavities loaded with Magnetic Alloys for Synchrotrons", Proc. of 1999 PAC, 1999.
[5] R. Muramatsu et al., "The First Beam Acceleration Test using High Gradient Cavity at HIMAC", Proc. of 1999 PAC, 1999.
[6] M. Yamamoto et al., "Multi-Harmonic Acceleration with High Gradient Cavity at HIMAC", Proc. of 1999 PAC, 1999.
[7] M. Fujieda et al., "Study of Adiabatic Condition on Beam Compression with Barrier Bucket", in this conf.