BEAM LOADING COMPENSATION USING PHASE TO AMPLITUDE MODULATION METHOD IN ATF

S. Kashiwagi, The Graduate University for Advanced Studies, Ibaraki, Japan
H. Hayano, K. Kubo, T. Naito, K. Oide, T. Shintake, S. Takeda,
N. Terunuma and J. Urakawa, KEK, Ibaraki, Japan
T. Korhonen, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
S. Nakamura, Yokohama National University, Kanagawa, Japan

Abstract

For future linear colliders, one of the essential techniques to get a sufficient luminosity is to accelerate multi-bunch beam of small bunch spacing. Beam loading voltage in an accelerating structure generates a large energy spread along the bunch train. This energy spread is critical for the lattice design and, if not properly compensated, induces emittance growth and in turn lowers the luminosity. A method to compensate for beam loading effects in a multi-bunch beam is under development at Accelerator Test Facility (ATF) in KEK [1]. We will report the beam tests for early injection and a phase to amplitude modulation method using multi-bunch beam of 2.8 ns bunch spacing. This energy compensation method compresses energy spread of multi-bunch beam by changing the input rf waveform properly into accelerating structures.

1 INTRODUCTION

A scheme of multiple bunches (87 bunches) being accelerated on each rf pulse is adopted in the Japan Linear Collider (JLC) design [2]. This scheme improves the energy transfer efficiency from wall plug power to the beam and luminosity of the machine. However, it results in turn significant beam loading. In JLC, an energy spread which is generated by the beam loading has to be reduced to a few tenth of a percent.

There are several possible methods to compensate the multi-bunch energy spread with keeping bunch spacing constant, such as ΔF method [3], ΔT method and so on. The ΔF method is to use one or more accelerator structures running at the frequency slightly higher and lower than the fundamental frequency and roughly in 90 degree out of phase from the acceleration. The ΔT method is to inject a beam before an rf pulse has filled in an accelerating structure. Power efficiency of ΔF method is higher than ΔT method, however this method is only adaptive in case that the energy of beam drops approximately linearly as a result of beam loading.

On the other hand, the transverse emittance dilution due to a random misalignment A_{rms} of quadrupole magnets with respect to the beam is estimated approximately to be

$$\frac{\Delta\epsilon}{\epsilon} \approx \frac{A_{rms}^2}{2\gamma_0\epsilon_0}\sum_i \gamma_i\beta_i k_i^2 (\frac{\Delta E}{E})_i^2 \qquad (1)$$

where $\gamma_0\epsilon_0$ is initial normalized emittance and γ_i, β_i, k_i and $(\Delta E/E)_i$ are Lorentz energy factor, beta function, focusing strength of quadrupole magnet and energy spread at the i-th quadrupole in the linac, respectively [4]. Since the emittance growth is connected to the energy spread at each quadrupole according to Eq. 1, energy spread correction should be done locally at each quadrupole. The ΔT method which compensates an energy spread in every accelerating structure is the local compensation, while ΔF method compensates it through several quadrupoles in average. In the low energy part in the linear colliders, the local correction method will be an important method where $\Delta E/E$ is not enough small.

2 PHASE TO AMPLITUDE MODULATION METHOD ($\Delta\phi - A$)

The most simple compensation of the beam loading in ΔT method can be done by injecting the beam before the rf pulse has filled the accelerating structure. If we use this simple early injection method, the beam current at which the energy compensation acts effectively is limited to some range, and acceleration efficiency will be poor. We apply

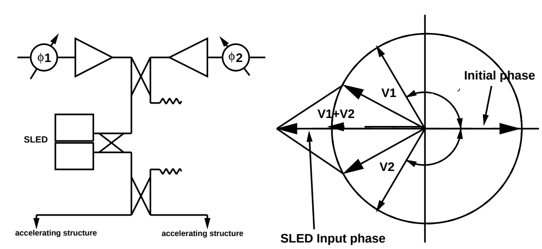

Figure 1: $\Delta\phi - A$ beam loading compensation

thus the amplitude modulation on the input rf pulse for the pulse compression. Therefore in case of using the SLED-I system [5], we can obtain the desirable slope of unloaded voltage by changing input rf waveform for SLED cavities. As discussed in Ref. [6], it is not a good idea to directly modulate the amplitude of the driving rf power to klystron. For a stable operation, a klystron usually needs to be used in the saturation condition. Thus, modulating the drive rf phase of klystron would be a better method. To modulate the amplitude of rf pulse for the SLED-I cavities at constant phase, two klystrons are needed. They run in saturation, keeping the input rf level constant. Then, we control their phases and combine the rf power from two klystrons by using a 3 dB hybrid combiner. Figure 1 shows a scheme in which the rf phases of two klystrons are rotated into opposite directions relative to each other. The sum of two phase modulated rf makes amplitude modulated rf with constant phase, which is fed into the SLED cavities. The phase modulation of the two klystrons effectively realizes amplitude modulation using this method ($\Delta\phi - A$ method).

If bunch population of each bunch is not uniform, thus the energy spread of beam does not drop linearly with time. Even in the case of it, phase modulation to amplitude modulation ($\Delta\phi - A$) method can properly compensate by changing the speed of phase rotation.

3 BEAM TEST OF $\Delta\phi - A$ ENERGY COMPENSATION

To verify that the $\Delta\phi - A$ beam loading compensation scheme works as predicted, we performed preliminary beam test in the ATF injector linac of the damping ring. The ATF s-band linac consists of 80 MeV pre-injector, 8 regular accelerating units, two units of energy compensating structure for ΔF energy compensation. Each regular unit contains SLED-I pulse compression system and the compressed rf power is fed into the two accelerating structures. For this experiment, the first and second regular sections were used and a chicane to measure the multi-bunch energy distribution was constructed downstream from this two regular units. ATF linac accelerates a multi-bunch beam that consists of 20 bunches with 2.8 ns spacing.

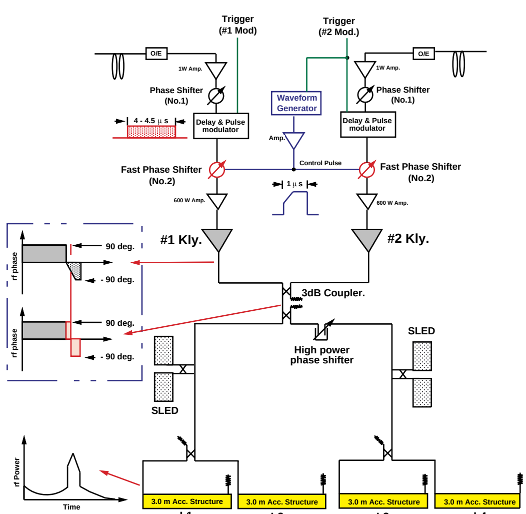

Figure 2: Experimental setup for $\Delta\phi - A$ beam loading compensation

3.1 Experimental setup

We preliminary tested $\Delta\phi - A$ method using two-klystron combination, Figure 2 shows the rf system of this experiment. It consists of two 85 MW klystron (TOSHIBA 3712), two dual-iris s-band SLED cavities, 3 dB hybrid combiner, high power wave guides, rf loads and an high power mechanical phase shifter. In this rf set up, rf power from the two klystrons were combined using 3 dB hybrid combiner, after that combined power was divided again to avoid a break-down at SLED cavities. High power mechanical phase shifter was used to adjust the relative phase between two rf units (L1,2 and L3,4 structures). Rf power is measured by using -70 dB Bethe-Hole coupler at several points which are each klystron out, the combined point, input of the SLED cavity and the entrance and exit of the accelerating structure. In the low level rf circuit, the 2856 MHz phase shifters (No.1) tune the rf phase of the input CW rf to the beam. By using Delay and Pulse Modulator, it is modulated into a short pulse with 4.5 μs width and the rf timing to klystron voltage is adjusted. The fast phase shifters (No.2) using varactor diode are used to rotate the drive rf phase. A control pulse with 1.0 μs width for the fast phase shifters is generated by an arbitrary waveform generator, and changes the rotating speed of drive phase. In this beam test, rotating speed of rf phase was changed at constant rate.

3.2 Measurement system of the beam energy

Figure 3 shows the layout of the beam line to measure the energy variation along the bunch train. For energy

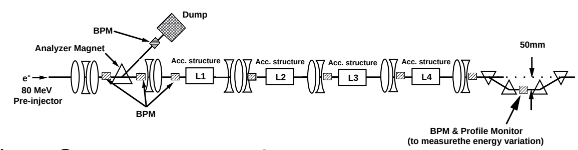

Figure 3: Beam line layout for energy compensation experiment

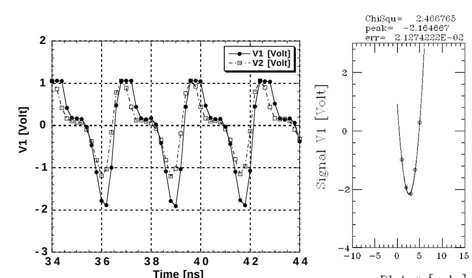

Figure 4: The beam signal from strip-line BPM and example of fitting to sample data

measurement, the horizontal chicane was installed down stream from the four regular accelerating structures which were filled amplitude modulated rf power. This chicane contains a strip-line-type beam position monitor (BPM) which is mounted at the center of the chicane to measure the beam energy. At this BPM, the horizontal dispersion function η_x is 50 mm. The multi-bunch beam signal from the BPM was measured by using a digital oscilloscope of real-time 5.0 GHz sample and a personal computer. A pulse height of each bunch signal was determined by a parabolic curve fitting to the sampled data. In this measurement, the position resolution was about 130 μm which was derived from three BPMs correlation and this position resolution corresponds to 0.26 % energy resolution. The position resolution was mainly limited by a systematic error of the fitting, so it may be improved using other functions for the fit. On the other hand, the only horizontal orbit of all bunches in the same pulse was measured using 7 BPMs in the linac, this measurement was free from the pulse-to-pulse energy jitter.

3.3 Preliminary result of beam test

In this experiment, the multi-bunch of 19 bunches/pulse accelerated with intensity of 0.82×10^{10} electrons/bunch at pre-injector exit. At the 80 MeV pre-injector, the energy of multi-bunch beam was compensated using the simple ΔT compensation technique (only early injection) to make the energy flat as an input of $\Delta\phi - A$ compensation section.

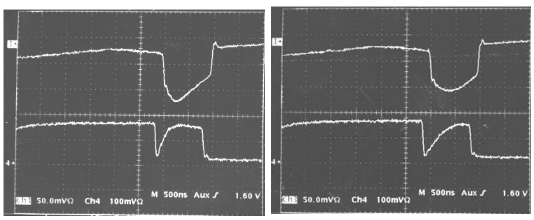

Figure 5: Rf waveform at the structure input (up) and the combined point (down) in different phase rotating speed. (right:90 deg./400 ns, left:90 deg./800 ns)

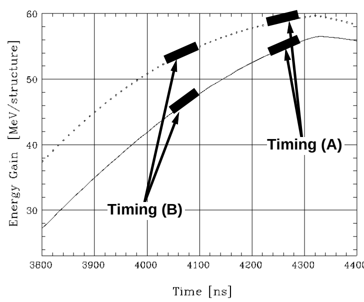

Figure 6: Calculation result of unloaded energy gain. Phase rotating speed are 90 deg./400 ns (dashed) and 90 deg./800 ns (solid)

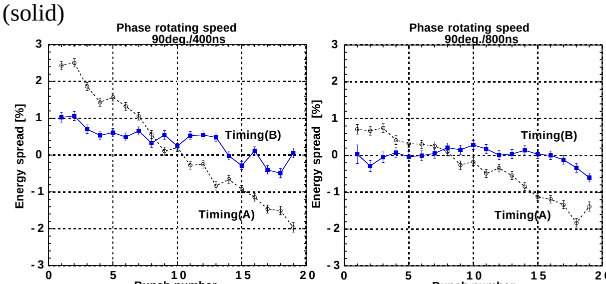

Figure 7: Measured multi-bunch energy spread with different phase rotating speed

We observed the difference of compensating voltage along the multi-bunch beam by changing the phase rotating speed and the relative timing of rf pulse to the beam in the two klystrons. Figure 5 shows rf waveforms at the input of accelerator and the combined point in the two cases of different rotating speed of drive rf phase. The calculation result of unloaded energy gain slope for the previous two different phase speed is shown in Figure 6. In this calculation, klystron output power is assumed to 20 MW which is the same value with the real beam test setup and the parameters of SLED cavities and structure are also the same. The two slopes of the unloaded energy gain curve are different by phase speed before first filling time of the structure. In the slow rotation case in which the phase speed is 90 deg./800 ns, the compensating voltage is larger than another case (see in Figure 6). Figure 7 shows energy distribution of multi-bunch beam in the two different rotating speed of drive phase and the two different beam injection timing to rf pulse which are shown as timing (A) and (B) in Figure 6. Assuming that the beam loss at $\Delta\phi - A$ compensation region was 10 % at the entrance of the first structure, the calculated beam loading voltage was about 2.7 MV/structure. Then the calculated energy spread with 90 deg./400 ns rotating speed are about 4.0 % at timing (A) and 1.8 % at timing (B), while in the another case with 90 deg./800 ns rotating speed they are about 2.8 % and 0.5 % at the each timing. From the Figure 7, the measured energy spread were 4.5 % (with timing A) and 1.5 % (with timing B) for 90 deg./400 ns, 2.6 % (with timing A) and 0.5 % (with timing B) for 90 deg./800 ns speed. The calculated values and the measured energy spread were consistent, so the amplitude modulation of the input rf acted to the multi-bunch beam so as to compensate the beam loading. However, the measured energy distribution inside the multi-bunch beam had a fluctuation from monotonous change. This fluctuation correlated to the intensity of each bunch. If we can measure the intensity variation along the bunch train and monitor the rf power correctly, the energy spread of multi-bunch beam will be minimized by setting the rotating speed of rf phase and injection timing as calculated. Its experiment is planed in this fall.

4 SUMMARY

The beam test of $\Delta\phi - A$ energy compensation was performed by using two klystron combination. Phase modulation of two klystrons was used to obtain an amplitude modulated input for the SLED. The modulation of accelerating waveform could be realized by modulating the amplitude of the SLED input. Energy gain of each bunch along a bunch train was changed by changing a rotating speed of an input rf phase, as a result the beam loading was compensated as expected.

5 ACKNOWLEDGMENTS

The authors would like to acknowledge the continuous encouragement of Professors M. Kihara, K. Takata, Y. Yamazaki. This experiment could not be performed without the help of Mr. D. Aizawa and E-CUBE corporation. We wish to thank these people for their help. The authors also appreciate to Drs. K. Egawa and M. Masuzawa of accelerator laboratory in KEK for the reason that they have readily lent us the dipole magnets.

6 REFERENCES

[1] F. Hinode et al, 'ATF Design and Study Report', KEK Internal95-4 (1995)

[2] JLC Design Study Group, 'JLC Design Study Report', KEK Report 97-1 A (1997)

[3] S. Kashiwagi et al., "Preliminary Test of $\pm\Delta F$ Energy Compensation System", Proceedings of the 18th Int. Linac Conf., Geneva, p.848 (1996)

[4] K. Kubo, Private communication

[5] P. B. Wilson SLAC-TN-73-15 (1973)

[6] T. Shintake, "C-band Linac RF-system for e^+e^- Linear Collider", Proceedings of RF96, April, 1996, Kanagawa, Japan, p37–46