Development of Multi-bunch Beam Energy Compensation Method

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Abstract

A method to compensate for beam loading effects in a multi-bunch beam is under development at Accelerator Test Facility (ATF) in KEK. In this paper we describe the rf high power test for ΔT energy compensation by using the SLED cavities. In this ΔT (early injection and amplitude modulation) energy compensation method, the input waveform into accelerating structure is changed by controlling the rf phase and combining the rf-power from two klystrons with a 3 dB hybrid combiner to compensate multi-bunch beam energy for various beam currents. In this test, an arbitrary waveform was generated by changing the rotating speed of the each klystron phase into the opposite direction and the beam test will be done soon.

1 Introduction

For future linear colliders, one of essential technique to get a sufficient luminosity is the ability to accelerate multi-bunch beam with small bunch spacing. In the linac of the KEK JLC design [1], the bunch train which is 85 bunches of 7.2×10^9 electrons/bunch and 1.4 ns bunch spacing. Beam loading voltage generates a large energy spread along the bunch train. In the S-band linac, as the pulse length of a multi-bunch beam is shorter than the filling time of accelerating structures, the energy gain of successive bunches drops by approximately linear function due to a transient beam loading in the accelerating structures. If this energy spread is not properly compensated, the emittance will grow by dispersion and chromatic effect in linac.

In this case it is necessary to compensate transient beam loading by some method. In linear collider the variation of bunch spacing is not acceptable, so the conventional energy compensation system (ECS) with four dipole magnets is not applicable. The ΔF energy compensation system (ΔF ECS) is tested at ATF which can compensate the multi-bunch beam energy by keeping the bunch separation [2]. This ΔF energy compensation method is to add two (or more) accelerating structures running at slightly higher and lower than the fundamental accelerating frequency and with roughly in 90 degree out of phase from the acceleration. On the other hand, the use of ΔT compensation method is also considerable in linear collider, this ΔT method is to inject a beam before an rf pulse has filled in an accelerating structure. In the low frequency (S-band) linac, average accelerating gradient and requirement of length of linac for the two compensating methods are roughly the same. The ΔF compensation method has a high flexibility for bunch population changes, and it is easier to tune. However, since ΔF compensation is not local correction, the alignment tolerance of the quadrupole magnet will be tighter than the ΔT compensation method. In addition, the ΔT method in different unit of accelerator is independent.

2 ΔT Beam Loading Compensation

The first order compensation of the beam loading can be done by injecting the beam before the rf pulse has filled the accelerating structure. The way that the ΔT compensation principle works is shown in Fig. 1, in which the voltage $V(t)$ produced by a square rf pulse is plotted as a function of time for a traveling-wave structure. The beam loading voltage $V_{bl}(t)$ is also plotted as a function of time. The resultant sum of $V(t)$ and $V_{bl}(t)$ is shown as the dashed line. The optimum injection time is determined by the $V(t)$ and $V_{bl}(t)$ slope. If we use this simple early injection method, the beam current at which the energy compensation can be comfortably performed is limited to some range, and acceleration efficiency will be poor. We apply thus the amplitude modulation on the input rf pulse for the pulse compression. Therefore in case of using the SLED system, we can obtain the desirable slope of unloaded voltage $V(t)$ by changing input rf waveform for SLED cavities. However, it is not a good idea to directly modulate the amplitude of the driving rf power to klystron. For a stable operation, a klystoron usually needs to be used in the saturation mode. Thus, modulating the klystron drive rf phase would be a better method. To modulate the amplitude of rf pulse for the SLED 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. Fig. 2 shows a scheme in which the rf phases of two klystrons are rotated into opposite directions relative to each other. The sum of two vectors is delivered to the SLED cavities. The phase modulation of the two klystrons effectively realizes amplitude modulation using this method. (PM-to-AM method)

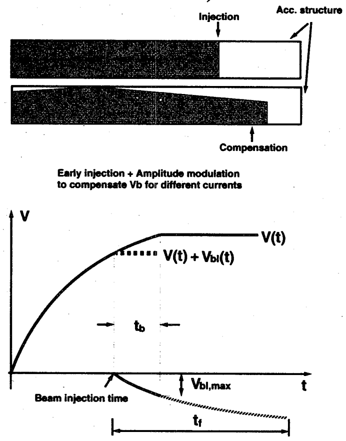

Fig. 1 Principle of the ΔT beam-loading compensation.

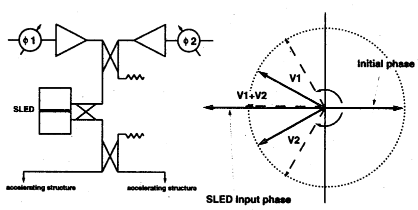

Fig. 2 Principle of phase modulation to amplitude modulation (PM-to-AM method)

2.1 Calculation of Energy Gain

The early injection and PM-to-AM energy compensation method can be applied to reduce the multi-bunch energy spread to a value even below that of the single bunch energy spread. Fig. 3 shows the calculation result for optimum compensation of the transient beam loading with SLED system, the multi-bunch energy spread is compressed less than 0.1%. If an accelerating structure with short filling time is used, the slope of the energy gain curve will be more flexible and rf power is saved than the case of the ATF structure (830 ns).

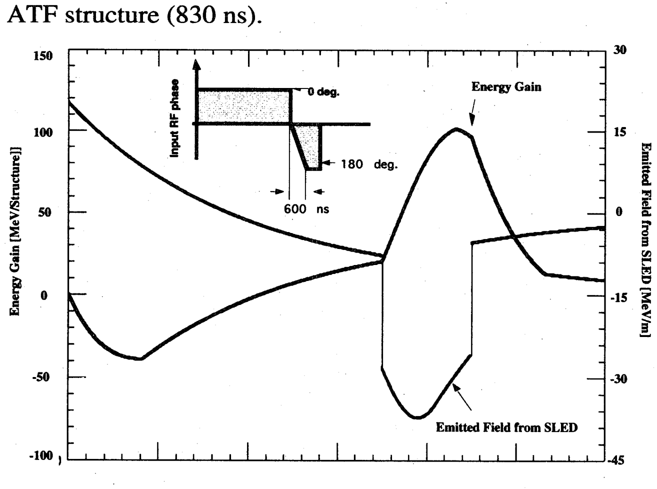

Fig. 3 Energy gain and output waveform of SLED (Each klystron output power : 30MW, the filling time of accelerating structure : 830 ns)

3 High Power rf Test for PM-to-AM

3.1 Experimental Setup

We preliminary tested PM-to-AM modulation using two-klystoron combination at ATF linac, Fig. 4 shows the high power rf test setup. It consists of an 85 MW klystron (TOSHIBA 3712), the dual-iris S-band SLED cavities, 3 dB hybrid combiner, high power waveguides, rf loads and vacuum pump system. In this rf test, rf power is measured by using -70 dB Bethe-Hole coupler at each klystron out, between 3 dB hybrid combiner and SLED cavity and the entrance of an accelerating structure.

The 2856 MHz reference signal was generated by multiplying the output signal of a 1428 MHz CW synthesized generator by 2. The 2856 MHz phase shifter (No. 1) tune rf phase to the beam. And by using Delay & Pulse Modulator, it is modulated into a short pulse with 4.5 μs width and the rf timing to klystron modulator main trigger is adjusted. The phase shifter (No. 2) is used to rotate the drive phase. A control pulse of the phase shifter is generated by combining two output pulse with 1.0 μs width of pulse generators (HP 8112A), and change a leading edge (LEE) of the other pulse generator as shown in Fig. 4.

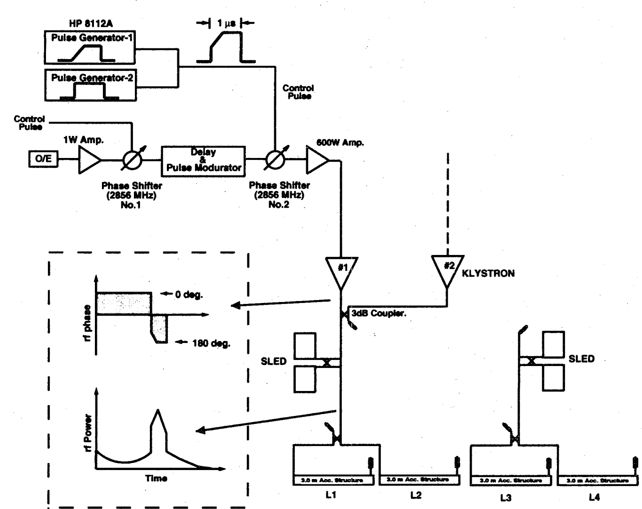

Fig. 4 High power rf test setup for PM-to-AM using two-klystron at ATF Linac

3.2 Experimental Results and Consideration

To combine the same rf power from each klystron, we measured rf power of each klystron at output of at 3 dB hybrid combiner and adjusted each klystron voltage. In this rf test the output power of each klystron was about 20 MW. Fig. 5 shows the obtained SLED output pulse. In the right side of Fig. 5 LEE of the pulse generator was set to 500 ns, however, it had actuary about 600 ns phase slope which is came from the slow response of the phase shifters.

The phase shifter in this rf test for PM-to-AM modulation is the reflection-type phase shifter using varactor diode. This type of varactor diode phase shifter is basically analog device in which the varactors function as variable reactance elements. This variable reactance is achieved through voltage-tuned capacitance of the diode under reverse-bias condition, therefore each of the rotating speed is different when the rf phases are rotated into opposite direction. Now we are planning to use the phase shifter which is I/Q phase shifter to vary the drive phase (Fig. 6).

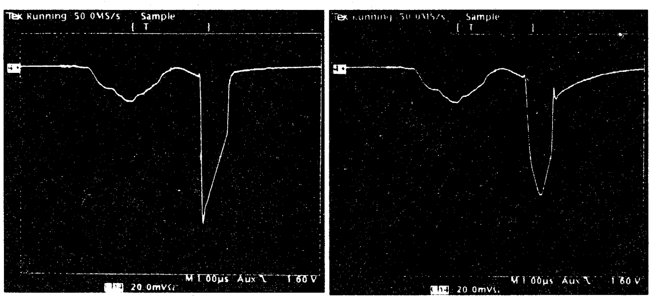

Fig. 5 rf waveform from SLED
(right : LEE=5.5 [ns] left : LEE= 500 [ns])

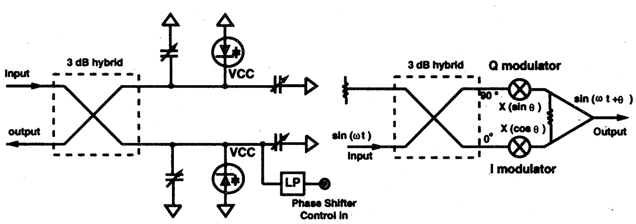

Fig. 6 The reflection-type phase shifter using varactor diode (left) and I/Q phase shifter (right).

4 Beam Test of ΔT Energy Compensation

To verify that the ΔT beam loading compensation scheme works as predicted, we are planning beam test at the first regular section of ATF injector linac. ATF linac accelerates a multi-bunch beam that consists of 20 micro-bunches with 2.8 ns spacing. Fig. 7 shows the layout and optics of the bean line to measure the energy variation along the bunch train.

For the energy measurement, the vertical chicane is made at down stream of an accelerating structure which is filled amplitude modulated rf power. This chicane contains a stripline-type beam position monitor (BPM) which is mounted at off-axis beam line to measure the beam position in linear sensitive region. At the this BPM, the vertical dispersion function (η_y) is about 20 mm. The multi-bunch beam signal from this BPM was measured by using fast sample hold (S/H) circuit and the digital oscilloscope of 5.0 GHz sample and changing the gate timing with 2.8 ns step for fast S/H. It is assumed that the position resolution of BPM is 11 μm, this value is achieved with 2.8 ns bunch spacing in ATF pre-injector linac [3] and correspond to 0.055% energy spread in the bunch train. If the beam position of many pulses is measured, statistically, resolution of the measurement will be improved.

On the other hand, in this beam test we will use the simple ΔT (only early injection) energy compensation technique to verify clearly the effect of PM-to-AM modulation method. At down stream of pre-injector the energy distribution in the bunch train is measured by using analyzer magnet and BPM. To achieve the loading compensation, the rotating speed of rf phase was configured based on the measured beam current and accelerator gradient which is calculated from monitored rf power. The timing of rf pulse relative to the beam in each klystoron is adjusted to minimize the energy variation along the bunch train.

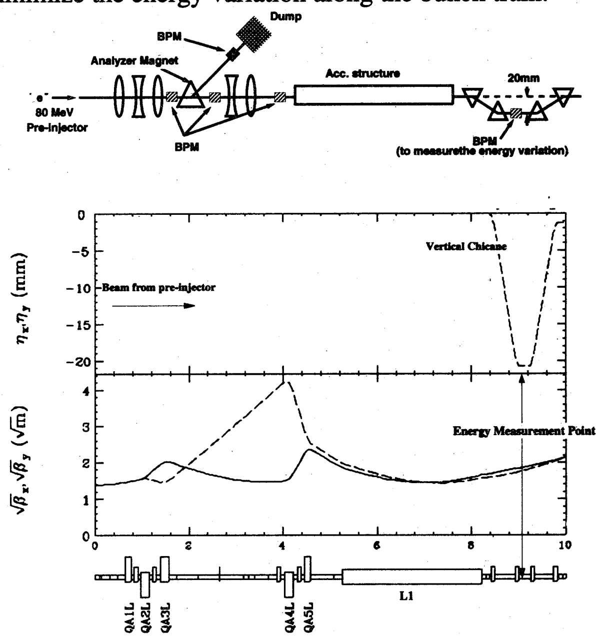

Fig. 7 Layout of beam line to measure the energy variation along the bunch train (up), and optics of beam line (down)

Conclusions

From this rf high power test, we need to develop the phase shifter which is good time response. To be easy the phase control and beam operation, it is necessary to develop the phase and energy feed-back system.

Acknowledgment

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