STUDY ON HIGH-CURRENT MULTI-BUNCH BEAM ACCELERATION FOR KEKB INJECTOR LINAC

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Abstract

The KEKB injector linac is usually operated to accelerate only two 10 nC electron bunches per cycle to generate positron[1], since more bunch cannot be equalized the beam energy using the conventional pulse compressor (SLED) and the simple phase flip. The aim of this study is to find how to accelerate more bunches without any modification of high power RF distribution. One way is that a part of the acceleration units is used to compensate for the beam energy difference. On the other hand, the recent electron linac is designed for multi-bunch operation by compensating for the beam loading. And this beam loading compensation method is usually realized by combining the output power of two or more klystrons. However one unit of our linac system consists of one 50 MW klystron in an acceleration unit. And eight units are fed by an 80 kW sub-booster klystron. Another way to realize the multi-bunch acceleration in our linac is using the amplitude modulation of the klystron. This can be realized using the fast I-Q modulation of the low level RF considering the non-linear characteristics of the total amplification system including klystrons. Further we developed a FPGA board with 100 MHz DACs and ADCs to achieve this.

POSSIBILITY FOR MULTI-BUNCH OPERATION IN KEKB INJECTION

The KEKB injector linac is usually operated to accelerate only two 10 nC electron bunches per cycle to generate positrons using the conventional pulse compressor (SLED) and the simple phase flip. Figure.1 shows the RF output of the SLED and the accelerating voltage of one accelerating structure. The duration of the bunches becomes 96 ns to syncronize two frequencies, 2856 MHz for the linac and 508.887 MHz for the KEKB ring. As shown in Figure.1, the acclerating voltage for two bunches are balanced by adjusting the beam timing compensating for the beam loading effect.

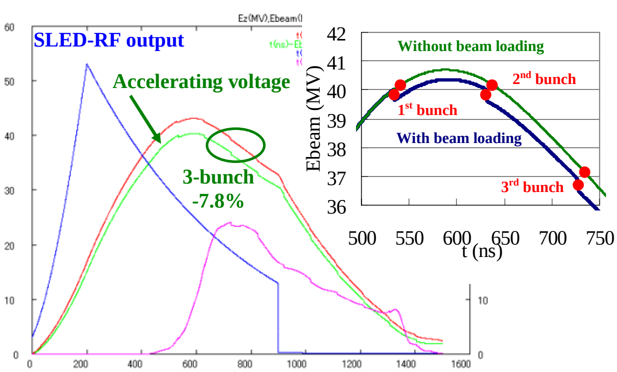

Figure 1: The SLED output and the acceleration voltage.

A simple way to increase the positron number is to increase the number of bunches. However if the third bunch is additionally injected into the waveform (Fig.1) of the accelerating gradient, the acceleration voltage is 7.8 % lower, where the third bunch is put in.

To increase the bunches without modification on the high power RF components, we can consider two methods as following,

- Three-bunch scheme: The simple phase flip is used for the SLED as the present operation except for some accelerating units to be used to increase the beam energy of the third bunch by adjusting the timing of the phase flip.
- Multi-bunch scheme: The fast phase modulation system is used to make the waveform to have the equal accelerating voltage for each bunch compensating for the beam loading effect.

3-BUNCH SCHEME

An easy way to increase the bunch number from two to three is that some accelerating units are used to accelerate the third bunch compensating for the lower accelerating voltage than for other bunches.

Simulation

The equivalent circuit simulation of the SLED and the accelerating structure were developed[2]. Figure 2 shows the equivalent circuit model of the coupled cavity chain.

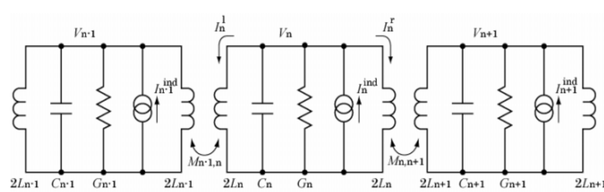

Figure 2: The equivalent circuit of the coupled cavities.

Calculated SLED output waveform using the simple phase flip and the total accelerating voltage corresponding to this SLED waveform are shown in Figure 1.

As shown in Figure 1, the accelerating voltage for the third bunch is 7.8 % lower compared with the first and the second bunch. However the 23 % of the accelerating structure need to be assigned for the compensation for the beam energy of the third bunch, because of the RF filling time (500 ns) of the accelerating structure is too slow compared with the duration (96 ns) between the second and third bunch.

LINAC Beam Test

We tested the 3-bunch scheme using the A and B sector of our LINAC as shown in Figure 3. An arc section called

J-Arc after the B sector enables to confirm if the beam energy of all these bunches is equalized.

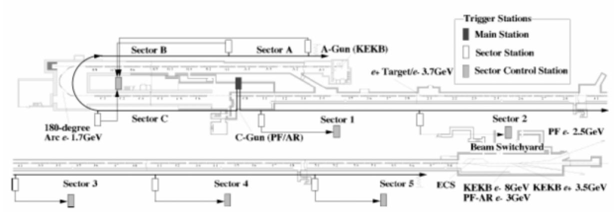

Figure 3: LINAC layout.

To balance the beam energy of the third bunch, the B-5 and B-6 units are used with an independent timing control system for these units. Figure 4 (left) shows the beam energy equalization by the equivalent circuit simulation.

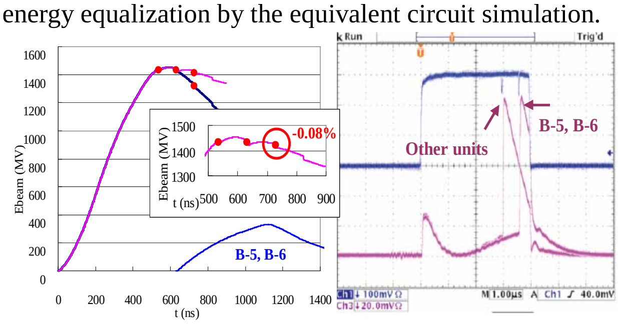

Figure 4: The beam energy equalization (left) and the SLED waveforms (right).

After we adjusted the timing of the B-5 and B-6 units to equalize the energy of three bunches, the RF output waveform of the SLED becomes as shown in Figure 4 (right).

The beam orbit of each bunch was observed using the beam position monitors (BPMs). Since the BPMs can monitor only two bunches at the same time, the trigger timing of the BPMs is changed corresponding to the observation of the first and the second bunch, or the second and the third bunch. Figure 5 shows the beam orbits and currents of the second and third bunches with compensation.

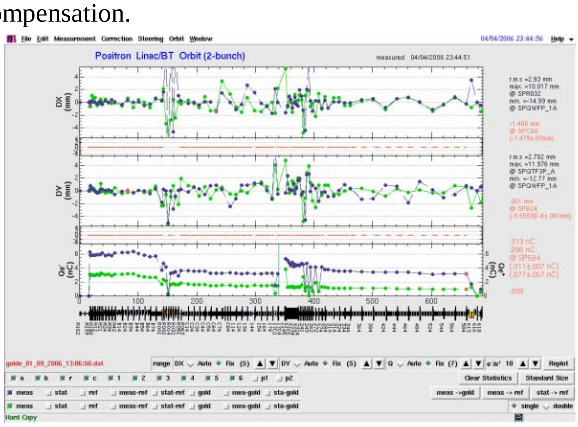

Figure 5: Beam orbits and currents of the second and third bunches with the energy equalization.

In this beam test, the total charge of the third bunch is setted to half of the charge of the first and second bunches due to the radiation restriction. However we will change the radiation restriction soon. After that, we will be able to inject 10 nC for the third bunch.

MULTI-BUNCH SCHEME

The 10 nC multi-bunch beam whose duration is 96 ns means the beam current of 100 mA. When such the beam current exists, the accelerating voltage will drop due to the beam loading effect. One of the ways to obtain the equalized accelerating voltage compensating for the beam loading is that the electric field shape considering the beam loading is made in the accelerating structure before the beam is coming. The electric field shape is the same field shape as in the steady state having the fixed beam current. This electric field shape is corresponding to that the input RF power must be modulated like a trapezoid shape. This beam loading compensation method was planned to be used in the normal conducting linear collider project such as the GLC project[3]. However, there is no existing linac using such a method.

Simulation

To make such trapezoid RF waveform using a conventional SLED, the RF amplitude of the klystron output must be modulated fast. The maximum gain in the pulse compression is estimated through the similar simulation described in the previous section. Figure 6 shows the SLED RF output for the beam loading compensation corresponding to three bunches (left) and five bunches (right). The accelerating voltage corresponding to these RF inputs are shown in Figure 7.

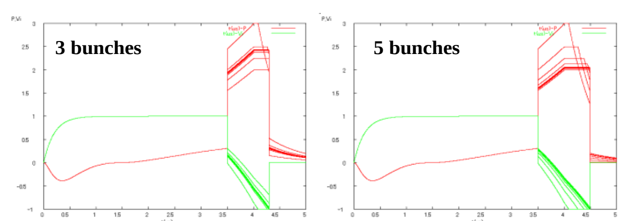

Figure 6: The SLED output corresponding to the amplitude modulation of the klystron for up to three bunches (left) and up to five bunches (right).

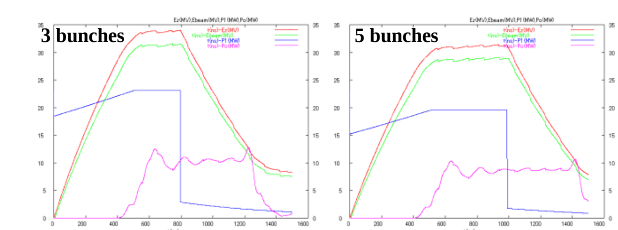

Figure 7: The accelerating gradient corresponding to the maximum SLED output with the beam loading compensation for up to three bunches (left) and up to five bunches (right).

Fast Phase Modulation System

The amplitude modulation waveform of the klystron output was determined through previous simulation. However an unit of our linac RF system consists of eight 40 MW klystrons which are fed by a 80 kW sub-booster klystron. Therefore we can only modulate the low level RF amplitude for each sub-booster klystron. The additional circuit as shown in Figure 8 is used for the fast modulation of the low level RF. It consists of a FPGA, D/A converters, A/D converters and DBMs.

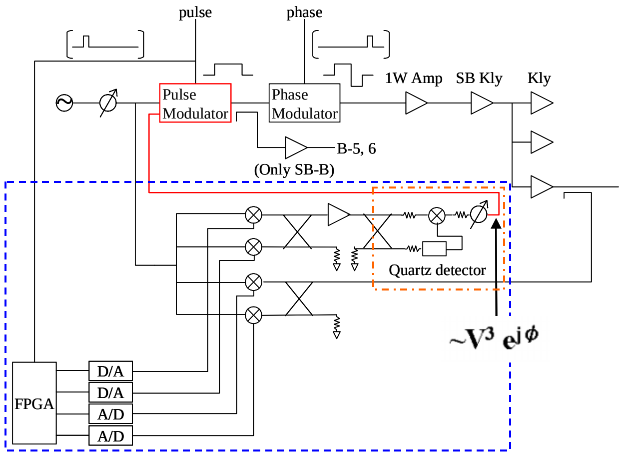

Figure 8: Fast modulation circuit of the low level RF.

In this fast modulation circuit, the most remarkable invention is the additional circuit which consists of the double balanced mixer (DBM) and a quartz detector. It works as the transmission characteristics of V^3. And it enhances the isolation and makes the transmission function more linearly through the non-linearity of the klystrons.

Amplitude Modulation of the Klystron

At the beginning, the saturation characteristics of eight klystrons must be equalized since the amplitude modulations of eight klystrons are combined to a low level RF modulation. After that, to determine the low level RF modulation waveform, we measured the transmission function from the low level RF modulation to the klystron output. Figure 9 shows the transmission function corresponding to the I and Q modulation respectively.

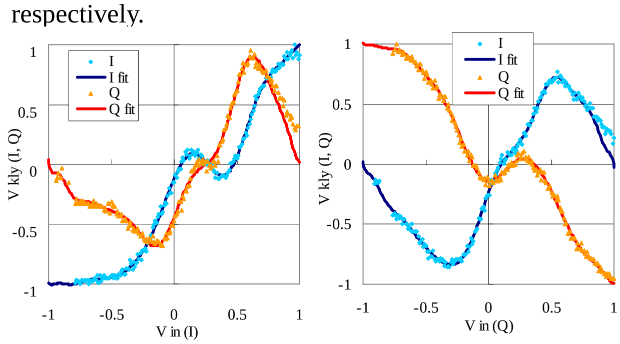

Figure 9: Transmission function from the low level RF to the klystron output.

To obtain the expected amplitude modulation on the klystron output, the low level RF modulation waveform was calculated using the transmission function. Figure 10 shows the resulted amplitude modulation of the klystron output (left) and the resulted SLED RF output (right).

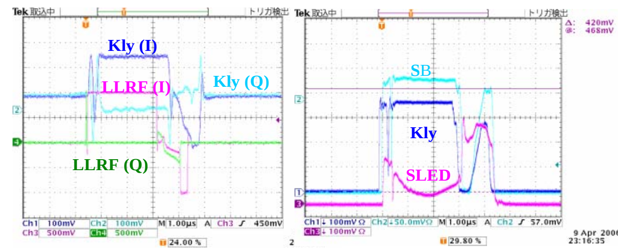

Figure 10: The obtained amplitude modulation of the klystron output (left) and the SLED RF output (right).

LINAC Beam Test

We also tested the multi-bunch scheme using the A and B sector of our LINAC. Figure 11 shows the beam orbits and currents of the second and the third bunch adjusting the trigger timing of BPMs to monitor the target bunches.

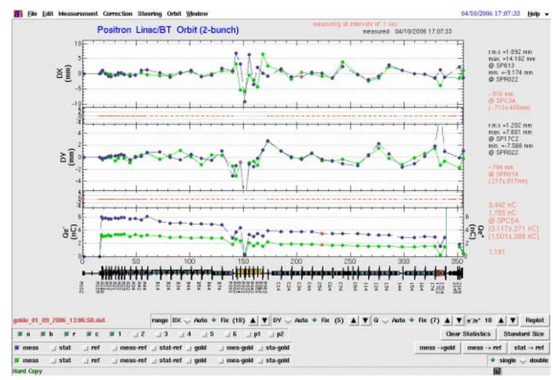

Figure 11: Beam orbits and currents of the second and third bunches.

SUMMARY

Both the 3-bunch scheme and the multi bunch scheme were demonstrated to be successful by the beam test.

For the 3-bunch scheme, the hardware modification is only to make the independent timing control system for a part of the accelerating units. However there is one difficulty in precisely adjusting the timing to operate this scheme stably.

For the multi-bunch scheme, the hardware modification is the additional fast modulation circuit for each low level RF driver of the sub-booster klystron, since the 50 MW klystron characteristics could be equalized in this test. Using this scheme, we can increase the number of bunches up to or over five. I plan to install the fast modulation circuit to all sub-booster klystrons.

REFERENCES

[1] Y. Ogawa et al., "High-Intensity, Two-bunch acceleration for doubling positron production at the KEKB linac", HEACC2001, Tsukuba, Mar 2001.

[2] M. Yoshida, "The research and development of high power c-band RF Pulse Compression System using Thermally Stable High-Q Cavity", Ph. D thesis of Univ of Tokyo, Dec 2003.

[3] "GLC Project Report", 2003.