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ENERGY COMPENSATION SYSTEM OF THE ATF LINAC

T.Korhonen, H.Hayano, H.Matsumoto, T.Naito, S. Takeda and J.Urakawa
KEK, National Laboratory for High Energy Physics
Oho 1-1, Tsukuba, Ibaraki 305, Japan

Abstract

A method to compensate for beam loading effects in accelerating multibunch beams at KEK-ATF is under development and ready for beam testing. The system consists of compensating sections used in addition to regular accelerating sections. The compensating cavities are operated with slightly different RF frequencies of 2856 ± 4.33 MHz. The system principles and the components are presented. The measured performance of the components and the status of the development are reported.

Introduction

One of the essential technical developments to get a sufficient luminosity in a linear collider is the ability to generate and accelerate multibunch beam trains. In the ATF [1] that is a test site for a future linear collider, this technique is tested by accelerating bunch trains that consist of 20 micro-bunches with small (2.8 ns) intervals (figure 1).

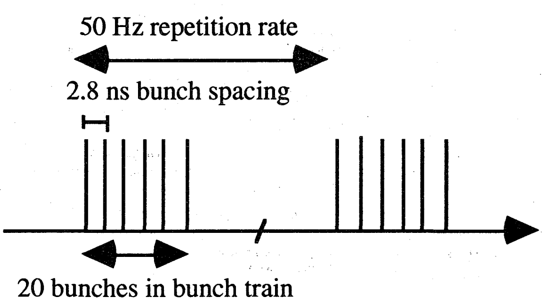

Figure 1. Beam structure of ATF.

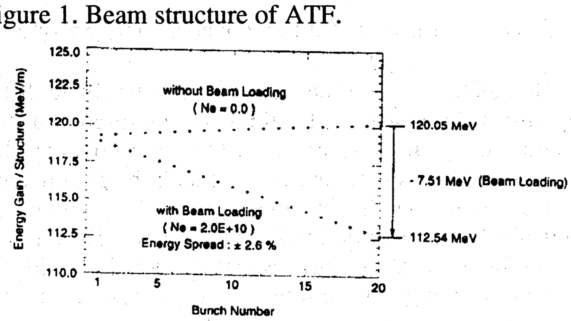

Figure 2. Beam loading in the ATF linac

As the bunch trains are accelerated, the energy gain of successive bunches reduces due to beam loading in the accelerating structures. The difference in energy gain between the first and last bunch is about 7.5 MeV / accelerating section (figure 2). After acceleration in the 1.54 GeV linac, the bunch trains are injected into a damping ring (DR). The energy acceptance of the DR is only 1%, because of the necessity to generate extremely low emittance beams required in a linear collider. This means that beam loading compensation system is necessary in ATF for successful operation of the multibunch scheme.

Due to the multibunch beam structure conventional energy compensation methods are not applicable and a novel one is going to be used in the ATF. In this method, "compensating" cavities are installed between the regular accelerating sections. These cavities are driven with a RF frequency that is slightly different from that used in regular sections. When entering these cavities, successive bunches of the train ride on of a different phase of the accelerating field (figure 4).

Due to this phase difference, the energy gain of the successive bunches is different. The energy spread is reduced as the first bunch enters to a decelerating phase and for the successive ones the energy gain is larger as the phase approaches the RF field peak. The amount of compensation can be controlled by changing the amplitude and the relative phase between the compensating and regular sections.

Two frequencies (f+Δf, f-Δf) are needed to compensate for the single-bunch energy spread. When bunches with non-negligible length pass through a rapidly changing field, the energy gain will be different for the bunch head and tail and thus the bunches tend to spread. With two frequencies the bunches enter into opposite slopes (rising/falling) of the accelerating field and the net effect is similar to acceleration with a flat-top pulse.

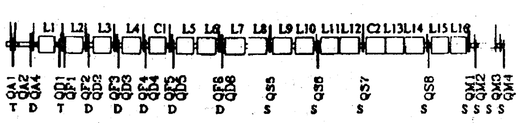

Figure 3. Lattice of the ATF linac (L0-L16 regular sections, C1,C2 compensating sections).

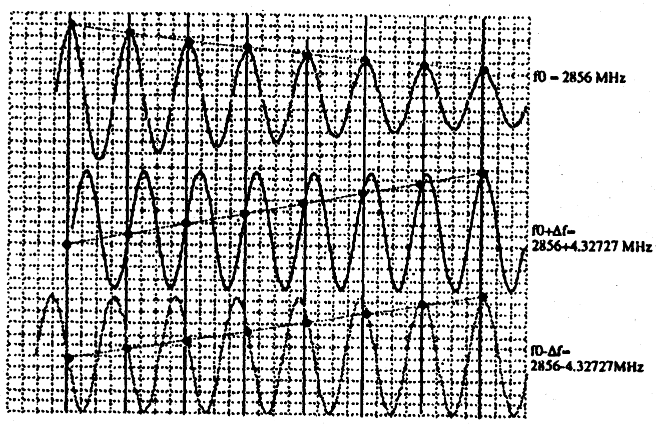

Figure 4. Principle of the energy compensation.

Compensation efficiency

In the ATF there are 16 regular sections and the compensating sections are installed between them as shown in figure 4. The spread in energy gain between the first and last bunch is 7.5 MeV/accelerating section. Without any correction, the spread would be roughly this times the number of accelerating sections, i.e. 120 MeV. An estimation of the efficiency can be calculated as follows. The time difference between the first and last bunches is t = (19*2.8ns) = 53.2 ns. With the sideband frequency of 4.327 MHz, length of one cycle (360 degrees) is 231 ns. This means that the difference between the phase in which the first and last bunches enter into the compensating section is 82.9 degrees. The maximum input power to the compensation cavities is 50 MW, and the maximum accelerating gradient is 26 MeV/m. With these conditions, the energy spread can be reduced from ±2.6% to ±0.2 % peak-to-peak with beam intensity of $2 * 10^{10}$ particles/bunch [1].

Timing

This energy compensation scheme is conceptually simple but demands very stable reference signals for the compensating sections. In contrast to typical beam acceleration where particle bunches are injected onto the crest of the RF wave, in the compensating system the bunches enter into a phase where the accelerating field changes rapidly (see figure 4). This means that even small changes in the signal phase cause a large error in the energy gain of the particle bunch.

The sideband frequency for the compensation was selected to be 4.327 MHz, twice the revolution frequency of the damping ring, to reduce the number of frequencies in the ATF timing system.

The requirements for the reference signal generation method are sufficient reduction of unnecessary sidebands and phase stability. After considering various possibilities, a method called phasing single sideband modulation was chosen. The principle of this method is rather simple (see figure 5). The fundamental (2856 MHz) and the sideband (4.327 MHz) signals are first split into two parts that differ 90 degrees in phase and then fed into dual balanced mixers. The output from the mixers is a product of the input signals, which by a trigonometrical identity can be expressed as a sum of two sinusoidal signals, with frequencies f+Δf and f-Δf, i.e. the desired sideband frequencies. One pair of the sideband signals is in equal and the other pair in opposite phase. When they are added in a signal combiner, the sideband with opposite phases cancels out and only the desired sideband remains. By reversing the signals from one of the quadrature phase shifters, both sidebands can be generated.

This method has also a further advantage of being feasible with even smaller sideband frequencies, where methods like using bandpass filters become exceedingly difficult. If this energy compensation method is going to be used with longer pulse trains, a lower sideband frequency is required to keep all the bunches within 90 degrees (unless the bunch spacing is changed).

We further employed a carrier suppression method to reduce the level of the carrier frequency, that inevitably "leaks" through the mixers.

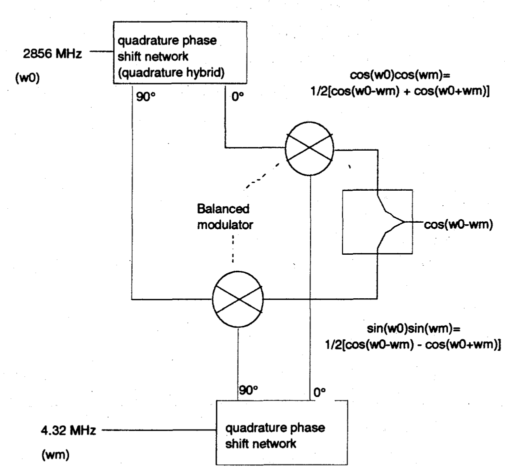

Figure 5. Principle of the sideband signal generation.

This technique is often considered to be difficult to implement. In typical applications it is required that the quadrature signals a wideband at the low frequency. In our case the frequencies are fixed and all the parameters for the input signals like their power levels can be controlled. The method proved to be very effective for our application. Very pure reference signals could be generated using this method; some results from measurements with a spectrum analyzer can be seen in the figures 5 and 6. The unnecessary frequencies are suppressed by even 60 dB, which easily fulfills the calculated requirement of about 40 dB, with a good safety margin. In long term tests, due to temperature variations etc., the suppression ratios were found to drift a little but even then to stay over 50 dB.

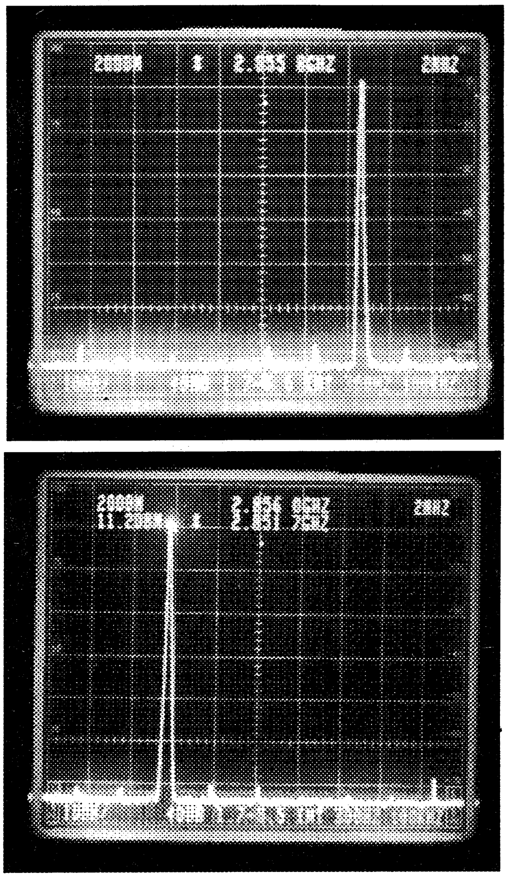

Figure 6 . Spectrum of the generated upper sideband signals (Above:upper sideband, below:lower sideband)

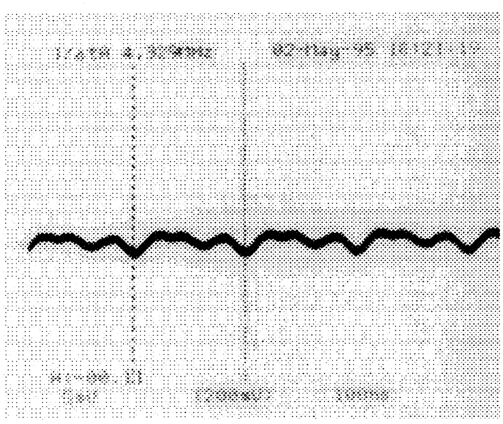

Figure 7. The measured phase jitter.

The allowed phase jitter of the reference signals is order of 1 ps). The jitter due to the reference signal generator was measured using two different methods to get a cross check. First method was to generate two signals of the same sideband and to feed them into a mixer. The mixer output is proportional to the phase difference between the signals and by watching the signal with an oscilloscope the phase jitter can be measured. The full width of the jitter measured with this method was 1.7 ps, and sigma = 0.8 ps (figure 7.). To cross-check this result, we used a HP oscilloscope to measure jitter. Although the measurement is approaching the limits of this oscilloscope, the results were consistent with ones obtained by the mixer method.

The Timing System

All the reference signals for the ATF are derived from one master oscillator where a 1428 MHz signal is generated. The S-band reference signal is generated by multiplying this frequency by two, and other necessary signals are generated by frequency division. The 4.327 MHz sideband signal is generated in a 1/165 divider from 714 MHz. The two compensating frequencies are generated in a module that has a duplicate of the previously described hardware.

The reference signals are distributed using a specially developed temperature-compensated optical fiber. The signal is first converted to light using electrical-to optical converter and then distributed using the optical fiber. The reverse conversion from light to electrical signals is done near each of the components requiring reference signals (klystron modulators etc.) [2].

Conclusions

The essential elements for the timing system are complete and components which fulfill the design requirements have been successfully developed. Although the performance of the system as a whole has not yet been tested, the performance of the system should be sufficient for the ATF operation. The real performance of the system can be verified in beam tests in near future. The tests shall give us important experience about this technique and its application in building a linear collider.

Acknowledgments

The authors wish to acknowledge the continuous encouragement of Professors Y. Kimura and K. Takata. and the whole ATF group.

Special thanks are due to Keith Jobe and Marc Ross of SLAC for various discussions about the system and valuable advice considering the tolerance calculations and the performance measurements.

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3. T. Korhonen et.al. R&D of the ATF Timing System. Proc. Intl. Linac Conference (LINAC94)