ENERGY EQUALIZATION BY USING S-BAND AND X-BAND ACCELERATOR MODULES

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Abstract

To reduce the beam loss and to restrict the expanse of the bunch length of the positron beam from the KEKB injector, an energy spread of ± 0.25% or less is required for the beam-transport (BT) line of the KEKB ring [1]. Generally, a positron beam has a large energy spread because the original bunch length is large and all positrons do not see the same accelerating field. Thus, an energy compression system (ECS) that consists of a magnetic chicane and two 2-m S-band accelerating structures was implemented at the end of the linac and has been used, but it has a demerit that the beam bunch is lengthened [2]. In this paper, we propose a new method to suppress the energy spread without enlarging the bunch length. This method utilizes superimposed acceleration of the S-band modules and X-band modules.

ENERGY COMPRESSION BY USING DIFFERENT FREQUENCY

A large energy spread of a positron beam is due to a position dependence of the energy gain. Assuming that the energy gain of beam particles riding on the rf wave crest is to be E_{e+} at the end of the linac, the total energy gain of the linac can be approximately expressed as

$$E_{total\ gain} = E_{e^+}\cos(2\pi\frac{z}{\lambda_s}) \tag{1}$$

where z is the distance from the centre of the bunch and λ_s is the wavelength of the S-band frequency. Equation (1) signifies that a large energy spread of the positron beam is due to a position dependence of the energy gain, considering that its original bunch length is large. Therefore, the positrons away from the centre bunch require a higher electric field to compensate for the energy variation. A correction function can be obtained by the Taylor expansion up to the 2^{nd} order; it is proportional to the square of z, as follows:

$$E_{equalizer} = E_{e^+} - E_{e^+}\cos(2\pi\frac{z}{\lambda_s}) \approx \frac{1}{2}E_{e^+}(2\pi\frac{z}{\lambda_s})^2 \tag{2}$$

The correction function, which is proportional to the square of z, can be realized by superimposing a different frequency of the same energy gain as the S-band. It can be expressed as

$$\begin{aligned} E_{equalizer} &= \Delta E\cos(2\pi\frac{z}{\lambda_s}) - \Delta E\cos(2\pi\frac{z}{\lambda_a}) \\ &= \Delta E\cos(2\pi\frac{z}{\lambda_s}) - \Delta E\cos(2\pi\frac{z}{\lambda_s}\times k) \\ &\approx \Delta E\times\frac{1}{2}(2\pi\frac{z}{\lambda_s})^2(k^2-1) \end{aligned} \tag{3}$$

where λ_a is the wavelength of the rf frequency, which we try to use, also $\lambda_s = k\ \lambda_a$. To compensate for energy variation up to the 2^{nd} order, an acceleration of

$$\Delta E = \frac{E_{e^+}}{k^2-1} \tag{4}$$

is required from Eq. (2) and Eq. (3).

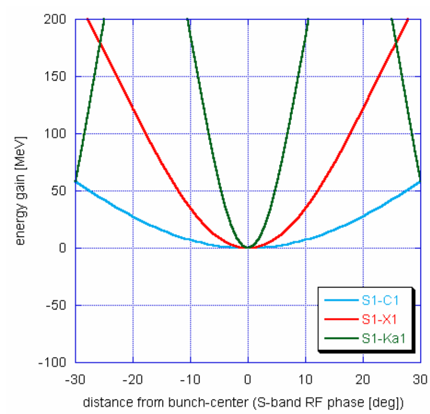

Figure 1: Comparison of the correction functions for three different frequencies with same energy, ΔE.
The legends of S1-C1, S1-X1 and S1-Ka stand for C-band (k = 2), X-band (k = 4) and Ka-band (k = 10), which are innovated for compensation, respectively.

Figure 1 shows that energy gain depending on the rf frequency which supplies the accelerating electric field when the correction function is obtained with the same energy, ΔE = 160 MeV corresponds to the energy of an accelerator module of the KEKB injector. This shows that a higher frequency is more effective for compensation than a lower frequency when comparing it with the same energy of the energy correction. For example, an energy of about 1166 MeV from the C-band (k = 2) module is required to compensate for a 3.5 GeV positron at the KEKB injector, while it is achieved by an energy of only about 233 MeV from the X-band (k = 4) module. Thus, in this method, innovating X-band modules is more practical than the C-band modules for savings in both cost and space. In addition, the aperture of a X-band accelerating structure is one 4th the size of the S-band accelerating

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structure, but the beam loss can be reduced by providing some focus coil. On the other hand, a correction of the higher order should be dealt with in the case of a higher frequency, as can be expected from Fig. 1.

SIMULATION AND RESULT

Performance of this energy-spread compensation scheme using S-band and X-band modules was evaluated by particle simulation in longitudinal phase space and was compared with that of the present ECS scheme.

Simulation

The beam energy distribution is calculated and simulations are based on Eq. (5) below, assuming that the particles are transferred from the focus system with a Gaussian distribution.

$$E_{total\ gain} = \sum_{i=1}^{n} E_i \cos(2\pi \frac{z_j}{\lambda_s} + \varphi_i) \quad (5),$$

where z_j is the particle position which respect to the bunch center, E_i is the energy gain of the S-band modules and φ_i is the accelerating rf phase.

The initial particles have 11 MeV of centre energy (1 σ ~ 2 MeV), 20 ps (FWHM) of bunch length and the number of particles is 10^4 for simulations. The particles are accelerated to the end of the linac with 25 S-band modules almost on their crest phases except for four center energy adjusting modules. Typical energy gain by an S-band module is 160 MeV.

Energy Compression System

In the KEKB injector, an energy compression system was implemented at the end of the linac to reduce the energy spread of the positrons from the linac by a factor of 1/2, to meet the energy acceptance of the BT line and the low-energy ring. The ECS is a phase space rotator which consists of a magnetic chicane by six bending magnets and two 2-m S-band accelerating structures. In the chicane, higher energy particles are forced to negotiate a longer path length than lower energy particles; particles of different energies traverse different path lengths. Thus, the path-length difference rearranges the relative longitudinal position of the particles in the bunch in correlation to their energies. After the chicane, the accelerating structures compensate the energy difference by dependence of energy gain on the positions of the particles riding on the rf wave. Figure 2 shows the particle distribution in the bunch (a) upstream of the ECS (at the end of the linac) and (b) downstream of the ECS. As Fig. 2(b) indicates, the bunch length is expanded through the ECS. In reality, the energy spread is also restricted by the diameter of the beam duct in the bending magnets which is limited by an energy acceptance of the ECS itself. Hence, beam loss by this acceptance is taken into account. Figure 3 shows the energy distribution in the bunch (a) upstream of the ECS and (b) downstream of the ECS. From this simulation, the ratio of a particle in the energy acceptance (± 0.25%) at the end of the linac to the initial particle is 44.2% and is improved to 74.1%, owing to the ECS. Since the acceptance of the bunch length is ± 6 mm (~ ± 2 σ) the ratio of an adequate particle ends up to be 65.2%.

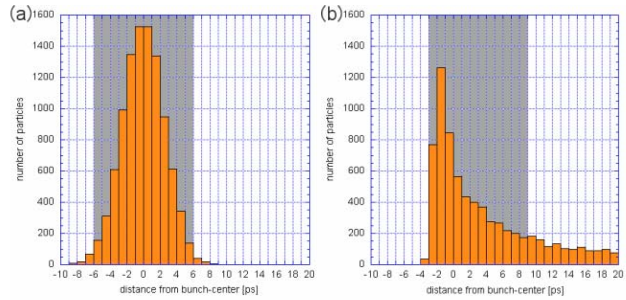

Figure 2: Longitudinal distribution of particles in the bunch. (a) upstream (at the end of linac) and (b) downstream of the ECS. The shaded region indicates the longitudinal acceptance of ± 6mm.

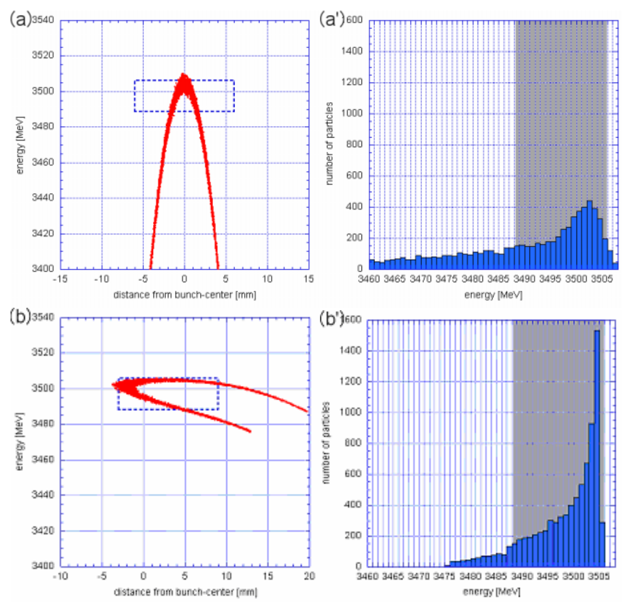

Figure 3: Phase space and energy distributions.
(a), (a′) upstream; (b) , (b′) downstream of the ECS. The dotted box region and the shaded region indicate the energy and the longitudinal acceptance of ± 0.25 % and ± 6mm, respectively.

Energy Equalization by Using an Accelerating Field of the S-band and the X-band

In this new scheme, cosine-like beam energy variation is equalized by using accelerating modules of different frequencies in the previous section. The advantage of this method is that the beam energy can be made uniform with the bunch length unchanged. We estimate the effect of a energy compression by simulations. The present KEKB injector accelerates positron beams up to 3.5 GeV with the S-band modules. For the energy equalization, the required energy gain of a X-band module is 233 MeV, from Eq. (4). The same energy gain is also required for additional S-band modules for energy equalization. A correction function is obtained by superimposing a deceleration by X-band modules and an acceleration by S-band modules.

Figure 4 shows the energy distribution obtained by using an energy compensation at the end of the linac. At the end of the linac, particles remaining in an acceptance of ± 0.25 are 44.2%, as shown in Fig. 3(a), but it improves to 92.6% with compensation, as shown in Fig. 4. This result shows that the compensation system (92.6%) can more capture particles than the ECS (65.2%).

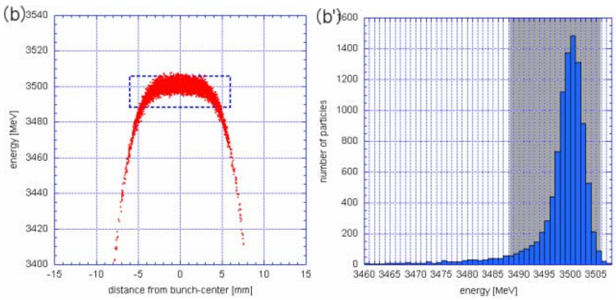

Figure 4: Phase space and energy distributions with the energy equalization by the S-band and the X-band accelerator modules. Jitter effects are not included.

Effect of RF Jitter

The effect of jitter, which originates in the accelerating rf source, must be considered in this method. The energy fluctuation is caused by the phase, power and timing jitter of devices, such as a thyratron, a klystron and an electron gun. These jitter effects can be approximately estimated from Eq. (5) by introducing a phase fluctuation, φ_i, from each sub-booster and klystron, a power fluctuation, E_i, from each klystron, and a timing jitter from the bunching section. In this simulation, suppose that the phase fluctuation is ± 0.1% and ± 0.63 ° for the sub-boosters and klystrons, respectively, the power fluctuation of the klystrons is ± 0.375% [5], and the timing jitter from the injection section is ± 1 ps. Each jitter is set in the simulation as a random number. Since jitters of the X-band module is not well known, they are assumed to be same as the S-band module at first. The simulation result is the average value of 25 sets of simulations. From the simulation, particle counts of about 3% are decreased in jitter compared with no jitter as for the case of the ECS scheme (62.0%), as shown in Fig. 5(a). In energy compensation with X-band modules, the particle counts of about 5% is decreased with jitter (87.4%) compared with no jitter. This result shows that energy compensation induces 1.7-times the jitter, as that of the ECS scheme. Another cases that jitters of the X-band module is assumed to be four-times as the S-band module, the particles remaining in the acceptance are reduced to 76.5%, as shown in Fig. 5(b). It is found that timing jitter in the X-band is the most serious issue for this compensation scheme.

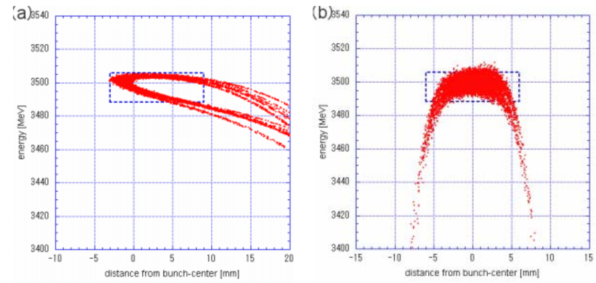

Figure 5: Examples of the energy distribution in a bunch while considering rf jitter. (a) used by only S-band modules and downstream the ECS (62.0%); (b) used by X-band modules that timing jitter is four-times as the S-band modules for compensation (76.5%).

CONCLUSION

It is shown that the superimposed acceleration of the S-band and the X-band modules can improve the energy spread of a positron beam more effective than the present ECS. To demonstrate a performance of this scheme with the existing equipments, we are planning an experiment by using the superimposed acceleration of the S-band and the existing C-band modules at the present KEKB injector instead of the X-band modules.

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