JP9611012

KEK Report 96-8
June 1996
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KEK--96-8
JP9611012

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Numerical Investigation of Transient Beam Loading Compensation in JLC X-band main linac*

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Abstract

In the present paper, two methods, "staggered timing" and "RF modulation", were studied for the transient beam loading compensation in the JLC X-band main linac. The inter bunch energy spread was found to be easily reduced down to less than ±0.06% with 10 sets of injection timings along the linac in the former case while with a simple linear ramping of the input RF voltage in the latter case. For both cases the energy transfer efficiencies from the power source to the beam were exactly the same. The tolerance of the beam intensity jitter was found to be ±1% for the multibunch energy spread of ±0.1%.

1. Introduction

Most of the present designs of the future linear colliders[1], except VLEPP, utilize multibunching in order to increase the luminosity and the energy efficiency with only extending RF pulse width. This multibunch scheme requires that the energies of the bunches in a train must be tightly controlled. To make the energy deviations of all the bunches within an acceptance of the final focus system and to keep the chromatic emittance dilution in the linac within an acceptable level, the bunch to bunch energy fluctuations need to be less than a few parts per thousand[2].

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* Work supported by the Japan Society for the Promotion of Science, JSPS/FF2/95044

Most of the methods to this aim utilize the idea to make the RF structure fill with a sufficient extra energy between bunch passage to make up for the decelerating fields deposited by the previous bunches in the train. A straightforward method is to modulate the input RF power to the structure. In the designs such as the NLC, the JLC(C), C-band design of JLC, and SBLC, it is considered to use the ramping of the output power from the RF power source to match the transient beam loading[2,3,4]. This method is called "RF modulation" in the present paper.

A similar effect is expected if the injection timing of the head bunch is properly adjusted with respect to the RF pulse[5,6]. However this scheme is practical only for a short bunch train, much shorter than the filling time of the structure if the compensation should be accomplished in a single accelerating structure. In the JLC(X), X-band design of JLC, the length of the bunch train is close to the filling time of the accelerating structure and then it becomes impossible to provide sufficient compensation within a structure. In this case was proposed an advanced timing strategy, "staggered timing"[2,4,7]. Also in the case of SBLC, the length of the bunch train is much longer than the filling time of the structure and the same method has been studied[8]. Here a number of structures, each with individual injection timing contributes to cancel the individual energy spread after the train passes through a series of the structures.

2. Method of structure simulation

As we concentrates only on the inter bunch energy spread, we start from the following approximations, which make the model of the structure simpler, i.e. easily computable, but do not destroy the picture of the processes. The approximations are (1) each bunch is considered to be a macro particle and rides on the crest of the accelerating wave, (2) the long range wake field of the accelerating mode is taken into account while neglecting the higher order modes, (3) the pulse shape given by the rise time or an intentionally applied modulation is considered and (4) the timing of the input RF pulse with respect to the beam injection timing is considered. Under these approximations, an N-cell accelerating structure was modeled as a series of wave guides from #1 to #N being separated by diaphragms with given reflection coefficients[9]. This situation is schematically shown in Fig.1. The cells #1 and #N are the coupler cells which are connected to the wave guides #0 and #N+1, respectively, with the proper coupling coefficients.

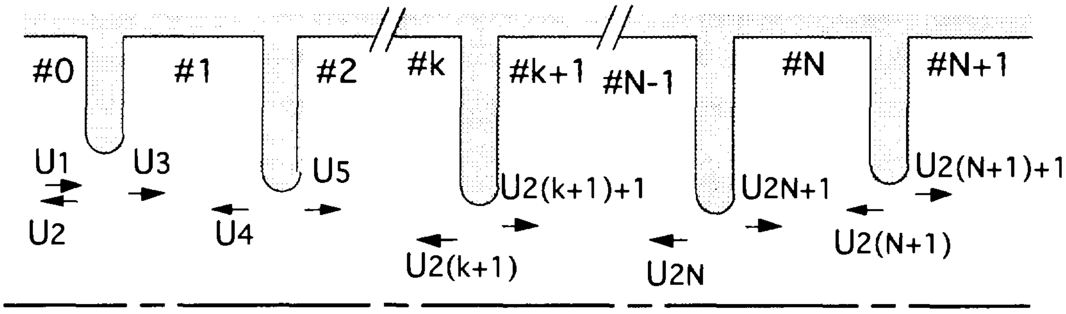

Figure 1. *Schematic drawing of the method.*

In this model, the propagation constant of the k-th cell is expressed as

$$\Gamma_k = -\alpha_k\, d + j\, \varphi, \tag{1}$$

where α_k is the attenuation parameter of the k-th wave guide, d the cell length and φ the phase advance per cell at the operation frequency. Each diaphragm can be characterized by the reflection coefficient r_k. Then, the transient amplitudes can be expressed as

$$\begin{aligned}
U^{RF}{}_0(\,t_i\,) &= (\,P_{in}(\,t_i\,)\,/\,P_0)^{1/2} \\
U^{RF}{}_1\,(\,t_i\,) &= U^{RF}{}_0(t_i)\;\exp(\,j\omega t_i\,) \\
U^{RF}{}_{2(k+1)}(t_i\,) &= -\,U^{RF}{}_{2(k+1)-1}(t_{i-1})\,\exp(\Gamma_{k-1})\,r_k \\
&\quad +\,U^{RF}{}_{2(k+1)+2}(t_{i-1})\,\exp(\Gamma_k)\,j(1-r_k{}^2)^{1/2} \qquad (2) \\
U^{RF}{}_{2(k+1)+1}(t_i\,) &= -U^{RF}{}_{2(k+1)+2}(t_{i-1})\,\exp(\Gamma_k)\,r_k \\
&\quad +\,U^{RF}{}_{2(k+1)-1}(t_{i-1})\,\exp(\Gamma_{k-1})\,j(1-r_k{}^2)^{1/2} \\
U^{RF}{}_j\,(t=0) &= 0\,; \qquad j=1,2,\ldots,2(N+1)+1,
\end{aligned}$$

where $U^{RF}{}_0(\,t_i\,)$ is the envelope of the incident RF voltage, $U^{RF}{}_{2(k+1)}(\,t_i\,)$ and $U^{RF}{}_{2(k+1)+1}(t_i)$ the amplitudes of the backward and forward waves around (k+1)-th diaphragm and $\Delta t = (t_i - t_{i-1}) = d/c$ for the case of relativistic bunches. The parameters α_k and r_k can be determined from the structure dimensions and losses.

To include the beam induced wake fields of the accelerating mode into the simulation we use the same equations as given in (2) by taking the discrete excitation of the accelerating cells with bunches. This excitation was expressed by adding the excited voltage to the right hand side of the amplitudes with a suffix of an even number in eq. (2) at the time when each bunch comes to the right-side diaphragm of a given cell as follows;

$$U^{W}_{2(k+1)}(t_i) = U^{W}_{2(k+1)}(t_i) + \Delta_{bn}\,\delta(t_i - T_{bn} - \Delta t\,k)\,(R/Q)_k^{1/2} \qquad (3)$$

$$U^{W}_{2(k+1)+1}(t_i) = U^{W}_{2(k+1)+1}(t_i)\ ,$$

where $\delta(x)$ is the delta function, T_{bn} the injection time of the n-th bunch and Δ_{bn} the beam loading parameter normalized to the first cell as

$$\Delta_{bn} = (q_n/2)\,(\omega\, v_{gr1} / P_0)^{1/2}\ , \qquad (4)$$

where q_n is the charge of the n-th bunch and v_{gr1} the group velocity in the first cell.

Before a realistic simulation, the relation between the group velocity in a structure of constant impedance and the reflection coefficient of the diaphragm was obtained[7]. The input and output reflection coefficient were determined so as to provide the good matching of the structure for the input and the output RF wave.

Now we shall demonstrate a simulation of the transient process in the JLC(X) detuned structure as an example.

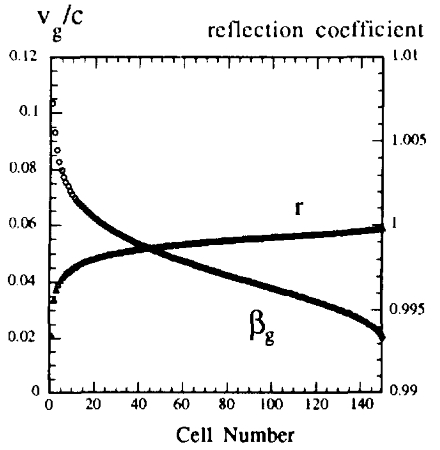

Figure 2. $\beta_g = v_g/c$ and reflection coefficient vs. cell number.

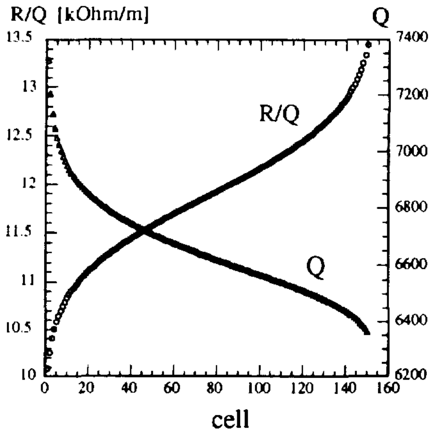

Figure3. R/Q and Q vs. cell number.

1. Using given geometry of the structure for the JLC(X), we first calculate the group velocity βg vs. cell number k and then obtain the reflection coefficients r along the structure in accordance with the results obtained at the previous stage, as shown in Fig. 2.

2. Next we calculate two more parameters vs. cell number, Q(k) and R/Q(k) (Fig. 3), and then obtain the distribution of propagation constant Γ_k along the structure as

$$\Gamma_k = -\omega/2Q_k\Delta t + j\varphi \ . \qquad (5)$$

3. Now we have the information enough to simulate the wake fields induced by the bunches in addition to the propagation of the RF pulse through the accelerating structure. Normalized accelerating field in the k-th cell at the moment $t = t_i$ can be obtained as

$$E_k^{RF}(t_i) = U^{RF}{}_{2(k+1)-1}(t_i)\,(R/Q)_k{}^{1/2} / S \qquad (6)$$

$$S = U_3(t{=}\infty)\,(R/Q)_1{}^{1/2} \ ,$$

where S is an coefficient that normalizes all the parameters to the first cell of the structure, $U_3(t{=}\infty)$ in a normalized amplitude of the forward wave in the first cell for the steady state regime and the value $U_{2(k+1)-1}(t_i)$ can be obtained from eq. (2).

On the other hand, the decelerating field induced by the bunches in the same cell is expressed as

$$E_k^{W}(t_i) = (\,U^{W}{}_{2(k+1)-1}(t_i) + U^{W}{}_{2(k+1)}(t_i)\,)\,(R/Q)_k{}^{1/2} / \ S \ , \qquad (7)$$

where the values $U^{W}{}_{2(k+1)-1}(t_i)$ and $U^{W}{}_{2(k+1)}(t_i)$ are obtained from eq. (3).

4. Now the loaded gradient of the n-th bunch within a train can be expressed as

$$E^{LD}{}_n = (2\pi/\lambda_0\,\{R/Q/\beta_{gr}\}_1\,P_0)^{1/2}$$

$$\times \sum_{k=1}^{N} (E_k{}^{RF}(t_n + \Delta t\, k) - E_k{}^{W}(t_n + \Delta t\, k)) / d$$

$$t_n = T_{b1} + T_s\,(n-1) \ , \qquad (8)$$

where T_{b1} is the injection time of the head bunch of the train and T_s the bunch spacing.

6. Finally the rising behavior of the input RF power, that is in most cases determined by the broad band properties of the RF amplifier, such as klystron, is defined as

$$U^{RF}{}_{0}(t) = (P_0)^{1/2} \left(1 - \exp(-t / t_f \; 2.3) \right). \qquad (9)$$

In this expression the parameter t_f is defined to be the time when the amplitude of the signal reaches 90% of its steady state value. This incorporation of the rising characteristics is quite important when we try to simulate transient processes in dispersive structures.

In Figs. 4 - 6 are presented the results of simulations for the JLC(X) detuned structure with an input RF power of 130MW to structure, an RF pulse duration of 250 nsec, a rise time of 20 nsec while no multibunch energy compensation was applied.

As we can see from Fig. 6, inter bunch energy spread due to the transient beam loading reaches up to 23%, that is several hundreds times higher than the linac acceptable level. In the following chapter are discussed the methods of how the beam loading can be compensated.

3. Compensation of multibunch energy distribution

The first method we tested is a ramping of the input RF power [2]. The basic idea of the method is to organize a modulation of the input RF pulse in such a way that the feeding RF power increases the amount equivalent to compensate the wake field of the

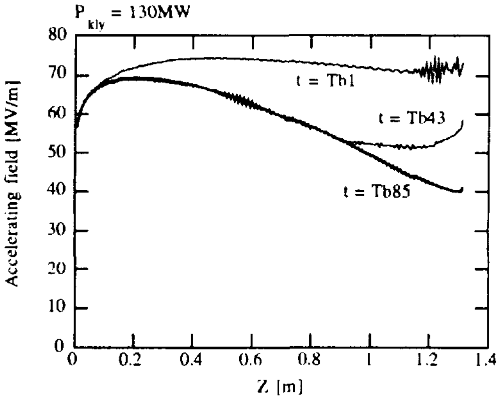

Figure4. Loaded accelerating electric field along the axis of the actual detuned structure at the times of the injection of different bunches in a train. Here the first bunch was injected just when the structure is filled with RF.

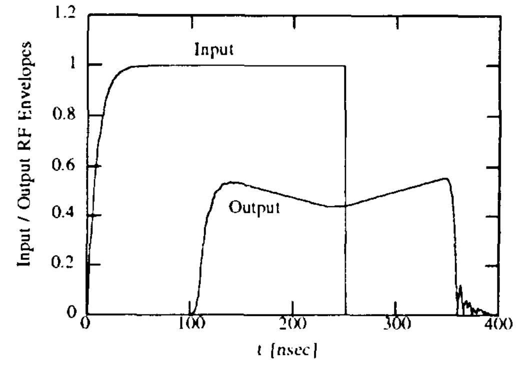

Figure5. Normalized input and output RF pulse envelopes with transient beam loading.

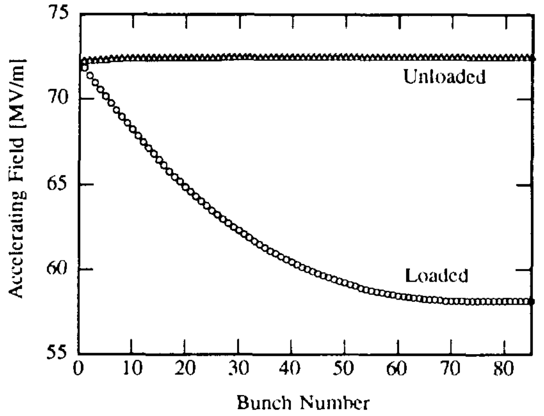

Figure6 . Unloaded and loaded accelerating gradient vs. bunch number.

preceding bunches during the period before the next bunch comes into the structure. The necessary duration of such a modulation is equal to the filling time of the structure. Just a linear growing of the amplitude of the input RF pulse is enough for such a purpose.

The second method, "staggered timing", is based on the individual timing for each accelerating structure. In this case the resulting energy spread is the sum of the energy distributions coming from passing through the structures in a compensation unit. If now every injection time of the first bunch in a train is chosen in an optimal way with respect to the time of the RF pulse input in each structure, one can expect the compensation of inter bunch energy distribution after passing the last structure in the unit. In Fig.7 are schematically shown the concepts of both methods.

Both methods were studied and optimized for the case of JLC(X) design parameters. The results of the optimized inter bunch energy spreads for both of the methods are shown in Fig. 8. For the staggered timing method we used 10 accelerating structures in a unit for the compensation. For the modulation scheme, the envelope of the amplitude of the input RF voltage was optimized as in Fig. 7(a).

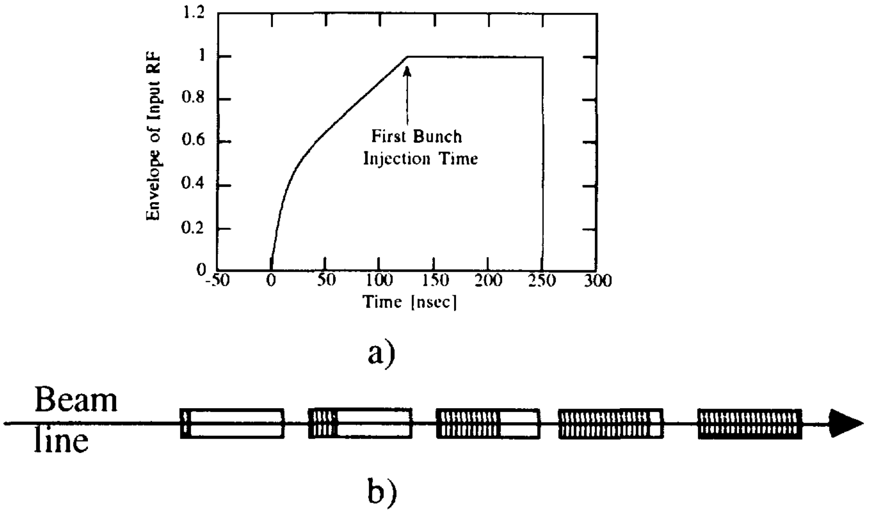

Figure 7. Two methods of multibunch energy compensation :

a) envelope of input RF pulse for "RF modulation" scheme.

b) "staggered timing" scheme; dark part corresponds to the part of the structure filled with RF at the time of the first bunch injection.

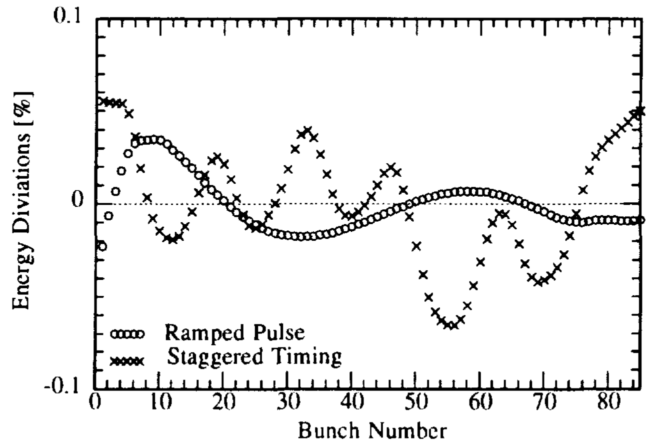

Figure8. Multibunch energy deviations in two different compensation methods.

The obtained energy spreads for both methods are better than ±0.06%, which is within an acceptable level. One of the important points in comparing the methods is the efficiency. Here we define the efficiency as the ratio of the energy extracted with the beam to the energy delivered to the structure from the RF source. Calculated efficiencies for both methods appeared to be exactly the same, 22.2%.

In Table 1 are listed the design values [1] and the parameters obtained in the present simulation. In the design values, the following assumptions were made; (1) the structure was assumed to be constant gradient type with the same number of cells and with the same total attenuation parameter, τ, to the actual detuned structure, (2) the dispersive effect of the structure and the RF pulse shaping were not taken into account, (3) the "staggered timing" scheme was applied for the multibunch energy compensation and (4) the single bunch beam loading was included. The results of simulation show a good agreement with the design parameters.

Table 1. Parameters for JLC(X) Linac.

Item	Design [1]	Present
Accelerating Frequency	11.424 GHz	<---
Operating mode	$2\pi/3$	<---
Structure Length	1.31 m	<---
Number of cells, N	150	<---
Group velocity, v_g/c	0.977 to 0.02	<---
Filling time , T_{fill}	110 nsec	106.2 nsec
Attenuation parameter	0.58	0.579
Bunch Number	85	<---
Single bunch population	0.7×10^{10}	<---
Bunch spacing, T_s	1.4 nsec	<---
Unloaded gradient	73 MV/m	72.5 MV/m
Loaded gradient on crest	58 MV/m*	58.1 MV/m**

* with (** without) including single bunch beam loading.

For staggered timing strategy the most severe problem is that the required level of energy spread is satisfied only just after passing the last structure in a unit for the compensation. If we take the injection timing in a simple order as the solid line in Fig. 9(a), then the energy spread in the intermediate stages can be very high as the solid line in Fig 9(b). However, if we choose a proper ordering of the timings, this effect can be significantly reduced. Finally the optimization of the order of the timing brought us the maximum energy deviations from 60% to 5% as shown by the dashed line in Fig.9 (a,b).

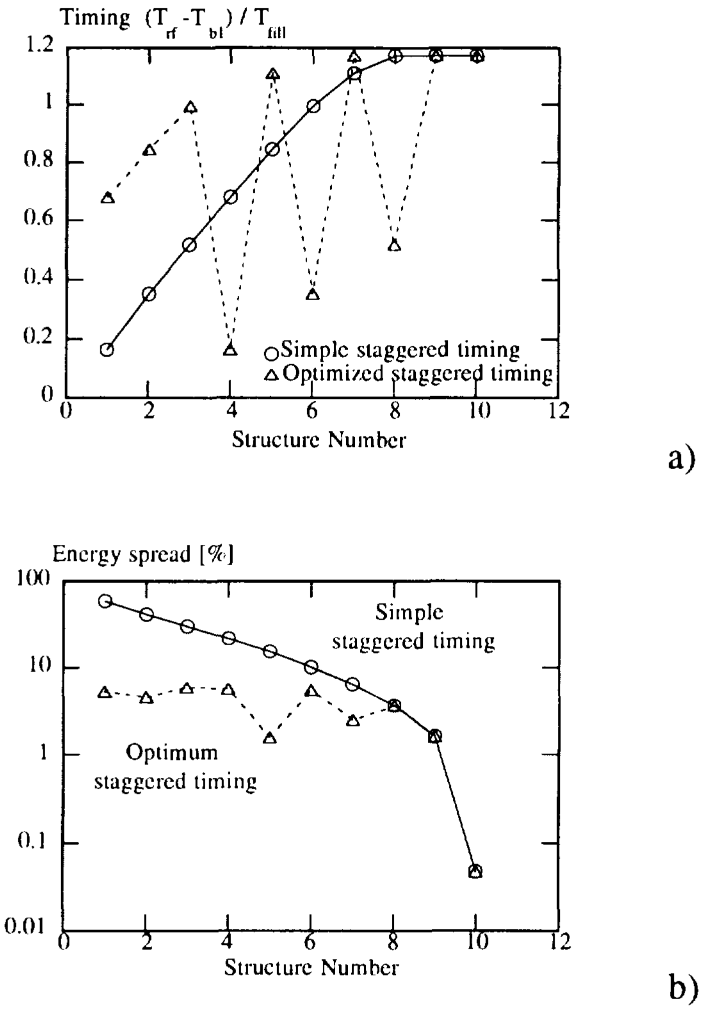

Figure9. *a) Initial and optimized orders of structure timings.*
b) Intermediate energy deviations.

To estimate the sensitivity of the energy deviation to the changes of design parameters, we calculated the growth of the multibunch energy spread due to the variation of the beam intensity as shown in Fig.10. In order to keep the acceptable level of the multibunch energy variations, the required tolerance of the beam charge was found to be better than ±1%. The corresponding tolerance of the RF power deviation is less than ±2%.

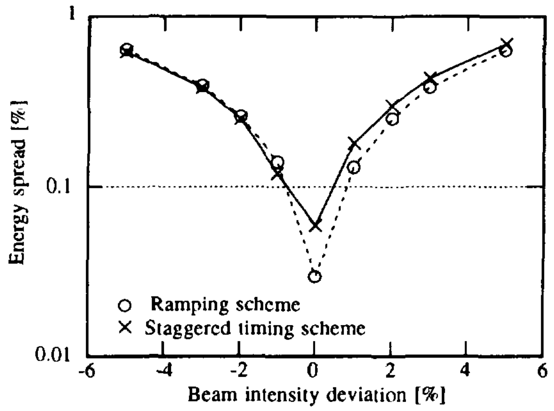

Figure 10. Compensated energy spread vs. variation of the beam intensity. Dashed line is for "RF modulation" method while the solid line for "staggered timing" method.

4. Summary and discussion

A simple method of the simulation on the transient processes in the accelerating structure is presented which does not require the direct computation of the electromagnetic fields. Therefore, the method is quite suitable for the fast checking of the beam loading and the externally fed RF properties in an arbitrary accelerating structure which can be expressed basically as shown in Fig. 1.

The two multibunch energy compensation schemes, "RF modulation" and "staggered timing", were found to provide an enough multibunch energy compensation for the linac and the final focus acceptance. The sensitivity against beam intensity or RF amplitude was found to be almost the same with each other.

In the "staggered timing" scheme, a special care should be taken as for the large multibunch energy distribution until the beam reaches the last structure in a compensation unit.

The simulation including the higher order modes is possible in the same manner as the present simulation but this is one of the future studies.

5. Acknowledgments

We greatly acknowledge Profs. K. Takata of KEK and V. Balakin of BINP for giving one of the authors a chance to work at KEK.

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