ANALYSIS AND MEASUREMENT OF FOCUSING EFFECTS IN A TRAVELING WAVE LINEAR ACCELERATOR

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Abstract

For a recent precise linear accelerator, such as an x-ray free electron laser facility, the beam orbit and the beam envelope should be properly calculated from the beam dynamics model of a traveling wave accelerating structure (TWA). In order to check the validity of the dynamics model of a TWA proposed so far, we compared a calculated beam orbit with an observed one in the C-band TWA section in SACLA. Although the beam orbit in the crest acceleration part was appropriately reproduced by the TWA model, the orbit in the off-crest acceleration part did not agree with the model calculation. We found out that the discrepancy came from a quadrupole field in the coupler cell of the TWA. The strength of the quadrupole field in the coupler was estimated by a three-dimensional rf simulation and the transverse dynamics model of a TWA was modified based on the simulation result. Consequently, the beam orbit was appropriately reproduced by the new model.

INTRODUCTION

The electron beam dynamics in recent precise electron linear accelerators, such as x-ray free electron lasers (XFEL), should be appropriately understood in order to predict the beam envelope and the beam orbit. In the XFEL facility, SACLA, for example, the beam energy is often changed to adjust the photon energy requested by an XFEL user. In such a case, the beam envelope in the undulator section should be calculated instantly and accurately for the transverse phase space matching to maximize the XFEL intensity.

For the precise calculation of transverse beam parameters in the accelerator section, in particular, the transverse dynamics model of a traveling wave accelerating structure (TWA) is important. The beam dynamics model of a TWA has been already proposed and such a model includes the effects of acceleration damping and edge focusing [1]. Therefore, this model has been applied to the TWA in SACLA and the beam envelope and the beam orbit have been calculated in various operation tools. In order to evaluate the validity of the dynamics model of a TWA, we compared a calculated beam orbit with an observed orbit in the C-band choke-mode accelerator section [2] in SACLA. An electron beam was slightly kicked by a corrector dipole magnet and the orbit distortion was observed by rf cavity beam position monitors (RF-BPM) [3]. Then, the calculated orbit based on the TWA model was compared with the observed orbit.

In this article, the transverse dynamics model of a TWA believed so far is summarized and the comparison between RF-BPM data and the calculation is discussed. Since the data implies that a TWA has a quadrupole focusing effect at an off-crest acceleration phase, this effect is estimated by using a three-dimensional rf electromagnetic field simulator. Finally, we propose a modified dynamics model of a TWA and we demonstrate that the modified model appropriately reproduce the beam orbit.

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BEAM DYNAMICS IN A TRAVELING WAVE LINEAR ACCELERATOR

In an ordinary transverse beam dynamics model of a TWA [1], following two effects are taken into account.

- Acceleration damping.
- Monopole focus at each end.

Therefore, we briefly introduce these effects in this section. Although a TWA has a ponderomotive focusing effect [4] due to the periodic component of the acceleration electric field, this effect is negligibly small for a high energy electron beam more than 100 MeV. Accordingly, we do not consider the ponderomotive focusing effect.

Hereafter, the direction of an electron beam is set to z axis, and the derivative of the transverse beam position x with respect to z is defined to be x'. The Lorentz factor is written by γ, and β is defined as $\beta = \sqrt{1-\gamma^{-2}}$.

Acceleration Damping

When an electron beam is accelerated, the longitudinal momentum is increased while the transverse momentum is conserved. Thus, x' is decreased and hence the beam emittance is damped. If the acceleration gradient is constant, the transfer matrix of this damping effect (M_{ACC}) can be written as [1],

$$M_{\mathrm{ACC}} = \begin{pmatrix} 1 & \dfrac{\beta_0\gamma_0}{\gamma' \cos\theta} \ln \dfrac{\gamma_1 + \beta_1\gamma_1}{\gamma_0 + \beta_0\gamma_0} \\ 0 & \dfrac{\beta_0\gamma_0}{\beta_1\gamma_1} \end{pmatrix}. \tag{1}$$

Here, β_0 and γ_0 (β_1 and γ_1) are Lorentz factors before (after) acceleration, γ' is the derivative of the Lorentz factor with respect to z, and θ is the rf phase of the beam with respect to the crest acceleration phase. The derivative of the Lorentz factor γ' can be represented by

$$\gamma' = \frac{eE_0}{m_e c^2},$$

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where e is the electron charge magnitude, m_e is the electron rest mass, E_0 is the acceleration electric field, and c is the speed of light in vacuum.

Monopole Focus at Each End

At each end of a TWA, the z component of the acceleration electric field immediately vanishes with increasing distance from the TWA. Because of the Gauss's theorem without any charge,

$$\nabla \cdot \mathbf{E} = 0,$$

the focusing electric field can be expressed by,

$$\frac{\partial E_\rho}{\partial \rho} + \frac{E_\rho}{\rho} = -\frac{\partial E_z}{\partial z}.$$

Here, the TWA is supposed to be axially symmetric and the cylindrical coordinate system (ρ, ϕ, z) is used. Supposed that E_ρ is proportional to ρ near the z axis (linear approximation), focusing electric field becomes

$$E_\rho = -\frac{\partial E_z}{\partial z} \cdot \frac{\rho}{2}.$$

At the entrance of a TWA, therefore, an electron beam is focused in both horizontal and vertical directions. On the contrary, the beam is defocused at the exit. Since the transverse force is the same for horizontal and vertical directions, this effect can be called as monopole focusing effect. By using a thin lens approximation, the transfer matrix of these effects can be written as [1],

$$M_{\text{in}} = \begin{pmatrix} 1 & 0 \\ -\dfrac{\gamma' \cos\theta}{2\beta_0^2\gamma_0} & 1 \end{pmatrix}, \tag{2}$$

$$M_{\text{out}} = \begin{pmatrix} 1 & 0 \\ \dfrac{\gamma' \cos\theta}{2\beta_1^2\gamma_1} & 1 \end{pmatrix}. \tag{3}$$

Here, we defined M_{in} and M_{out} as the transfer matrices at the entrance and the exit of the TWA, respectively.

COMPARISON BETWEEN DATA AND CALCULATION

In order to confirm whether the dynamics model mentioned in the last section is correct or not, we compared the calculated beam orbit with the observation. In the C-band accelerator section of SACLA, the field strength of a corrector dipole magnet was changed and the beam orbit distortion was observed by RF-BPMs. The transverse kick momentum was calculated from the relationship between the supplied current and the integrated B-field for each corrector magnet. The transfer matrix of the C-band accelerator was obtained from Eq. (1) – (3). For the other components, such as a quadrupole magnet, the transfer matrix is appropriately calculated from the design value of each component. By using these transfer matrices, the beam orbit distortion after the scanned corrector magnet was predicted.

First of all, the corrector magnet at the crest acceleration part was scanned and the result is plotted in Fig. 1. The observed beam orbit was properly reproduced by the calculation. Therefore, the beam dynamics model of a TWA at the crest acceleration phase is considered to be sufficiently correct.

Next, the corrector magnet at the off-crest acceleration part before a bunch compressor was scanned. The obtained beam orbit is plotted in Fig. 2. In this case, the beam orbit is completely different between the data and the calculation. Thus, the beam dynamics model of a TWA mentioned in the last section is insufficient for the off-crest acceleration phase. In fact, when the acceleration phase was set to crest for all the accelerator units, the beam orbit was properly reproduced. Therefore, a TWA has another focusing effect in case of the off-crest acceleration.

In order to correct the beam dynamics model of a TWA, at first, we modified the focusing strength at the entrance of the accelerator by multiplying a correction factor. As a result, the beam orbit was able to be reproduced by the correction factor and the factor was a function of the acceleration phase, as shown in Fig. 3. Furthermore, the slope of the correction factor was opposite between the horizontal direction and the vertical. This implies that a

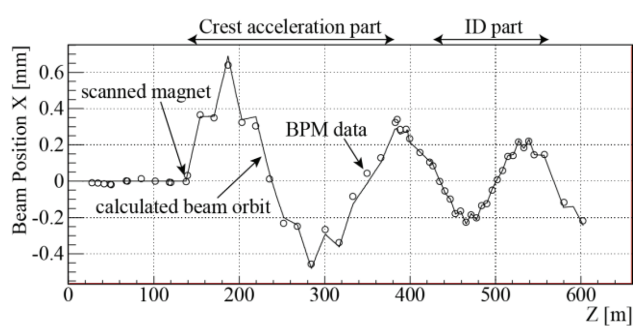

Figure 1: Beam orbit distortion induced by a corrector magnet in the crest acceleration part. The open circles are RF-BPM data and the solid line is a calculated orbit.

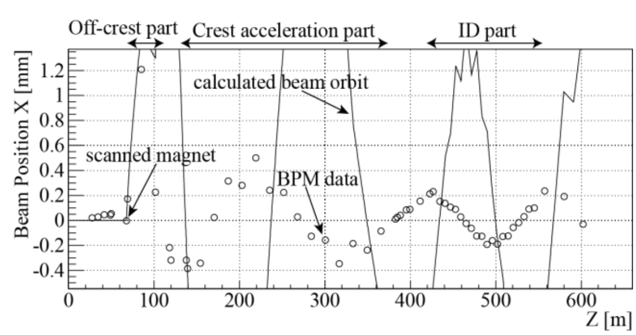

Figure 2: Beam orbit distortion induced by a corrector magnet in the off-crest acceleration part. The open circles are RF-BPM data and the solid line is a calculated orbit.

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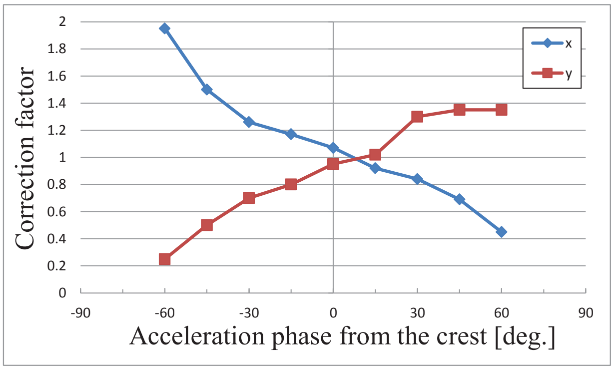

Figure 3: Correction factor for the edge focusing effect at the entrance of the traveling wave accelerating structure as a function of the rf phase. The horizontal axis shows a phase difference from the crest. The blue diamonds are the correction factors for horizontal focusing and the red rectangles are those for vertical focusing.

TWA has a quadrupole focusing effect in the off-crest acceleration phase.

ANALYSIS OF THE QUADRUPOLE FOCUS AT THE COUPLER

From the data in the last section, we considered that a quadrupole field was excited in the coupler cell of a TWA, since the coupler cell has an asymmetry due to the coupling hole with a waveguide. Therefore, we simulated the rf field in the coupler cell of the C-band choke-mode accelerating structure [2] by using a three-dimensional rf simulator, HFSS [5]. Figure 4 shows the side view of the analyzed model of the C-band accelerator. This model has two coupler cells and four regular cells between them. The coupler of the C-band accelerator has the J-type double feed shape [6] and the regular cell has a choke-mode structure [2] to damp higher order modes of a wake field. In this simulation, the electromagnetic field strength in the accelerator is normalized to the average acceleration gradient of 35 MV/m, which is a typical operation condition of SACLA.

The electric field and the magnetic field in the coupler cell are illustrated in Fig. 5. Since the coupler cell has two coupling holes, the electromagnetic field is elliptically distorted. This indicates that the coupler cell excites a quadrupole field in addition to a monopole field. Thus, we analyze the quadrupole field hereafter. For example, the transverse B-fields, $B_y(x)$ and $B_x(\mathrm{y})$, around the center of the coupler cell are plotted in Fig. 6. The quadrupole field can be expressed by $[B_y(x) - B_x(\mathrm{y})]/2$, while the monopole field is $[B_y(x) + B_x(\mathrm{y})]/2$.

The quadrupole electromagnetic force affecting to the electron beam at the zero-crossing rf phase is plotted in Fig. 7. The horizontal axis is the longitudinal position that is converted to the cell number. A significant quadrupole field is excited in the coupler cell. This field consists of a small electric field around each iris of the coupler and a large quadrupole magnetic field in the coupler cell. Moreover, the sign of the quadrupole field in the entrance coupler is the same as that of the exit. This situation is in contrast with the monopole focusing effect, which shows an opposite sign each other.

The quadrupole field strength at the crest rf phase is shown in Fig. 8. Although a quadrupole field is excited in the coupler cell, this field is canceled out in each cell and almost no quadrupole field remains. These behaviors are consistent with the data shown in Fig. 3.

The integrated quadrupole field strengths for the rf phases of zero-crossing, 45 degrees and crest are summarized in Table 1. In this table, the unit of the integrated quadrupole field is converted to Tm/m and the acceleration gradient is assumed to be 35 MV/m. These results indicate that the quadrupole field strength at the zero-crossing phase is approximately half of the monopole field at the crest phase. It is to be noted that the quadrupole field strength depends on the coupler shape. For the sign of the field strength, the quadrupole field shows the same sign for each of the entrance and the exit, while the monopole field shows the different sign, as mentioned above. Consequently, the quadrupole field is accumulated at each coupler and a significant quadrupole focusing effect can be observed at an off-crest acceleration phase.

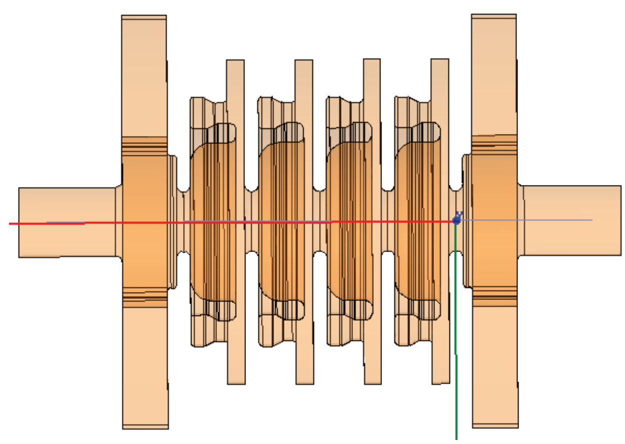

Figure 4: C-band accelerator model for three-dimensional rf field simulation.

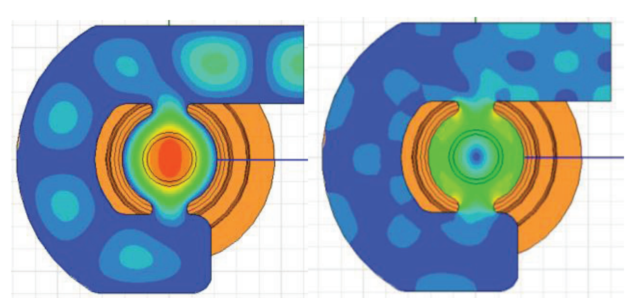

Figure 5: Contour plot of the E-field (left) and B-field (right) in the coupler cell.

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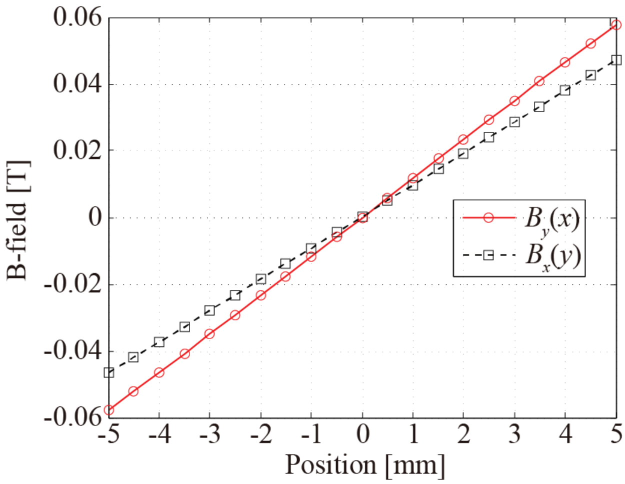

Figure 6: Transverse B-field in the coupler cell.

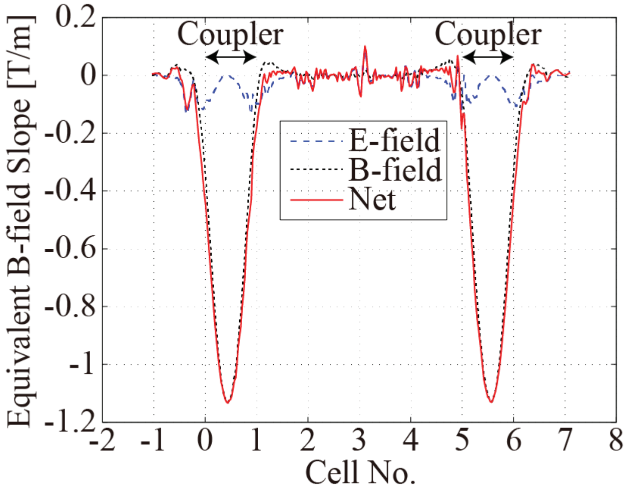

Figure 7: Quadrupole focusing field on the beam at the zero-crossing phase. The E-field strength is converted to the focusing field equivalent to the B-field.

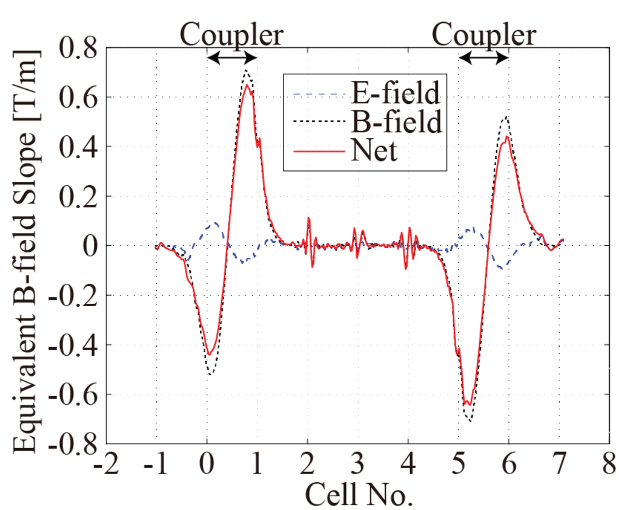

Figure 8: Quadrupole focusing field on the beam at the crest phase.

Table 1: Focusing Force in the Coupler Cell

Phase	Coupler	Monopole [Tm/m]	Quadrupole [Tm/m]
Zero-crossing	input	-0.0024	-0.0170
	output	-0.0001	-0.0166
45 deg.	input	-0.0247	-0.0117
	output	0.0220	-0.0122
Crest	input	-0.0326	0.0005
	output	0.0312	-0.0007

MODIFIED MODEL OF A TRAVELING WAVE ACCELERATOR

As a result of the analysis described above, we modified the transverse dynamics model of a TWA including a quadrupole focusing effect at an off-crest acceleration phase. The transfer matrices for the edge focusing effect, Eq. (2) and (3), are modified to be,

$$M_{\text{in}} = \begin{pmatrix} 1 & 0 \\ \left[\alpha_{\text{quad}} \sin\theta - (1+\epsilon_{\text{mono}})\cos\theta\right] \dfrac{\gamma'}{2\beta_0^2\gamma_0} & 1 \end{pmatrix},$$

$$M_{\text{out}} = \begin{pmatrix} 1 & 0 \\ \left(\alpha_{\text{quad}} \sin\theta + \cos\theta\right) \dfrac{\gamma'}{2\beta_1^2\gamma_1} & 1 \end{pmatrix}.$$

Here, α_{quad} is a coefficient of a quadrupole field, which depends on the coupler shape, and ϵ_{mono} is a correction factor for the monopole field at the entrance coupler. The reason for adding ϵ_{mono} is because the agreement between the data and the calculation becomes better when the monopole focusing effect is slightly corrected.

The beam orbit calculated by the new model is shown in Fig. 9. In this figure, the value of α_{quad} is set to approximately 70% of the simulation result (Table 1) in

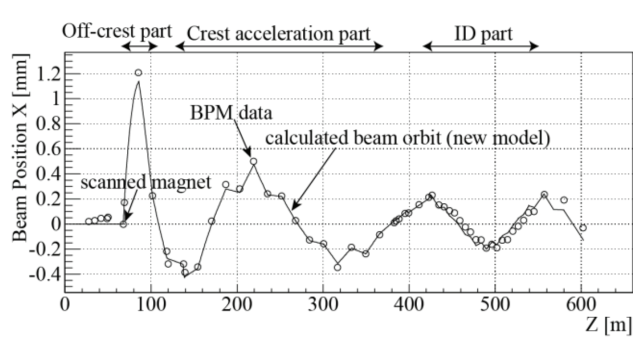

Figure 9: Beam orbit distortion induced by a corrector magnet in the off-crest acceleration part. The quadrupole focusing effect of the accelerator is implemented in the calculated orbit. The open circles are RF-BPM data and the solid line is the calculated orbit.

order to reproduce the data appropriately. The value of ϵ_{mono} is set to 0.03, so that both horizontal and vertical orbits agree with the data. By using the new model of a TWA, beam orbits for both the off-crest acceleration part ($z < 120$ m) and the crest part ($z > 120$ m) are properly calculated. Since the absolute value of the quadrupole force of the accelerator indicates a discrepancy between the simulation and the data, this is a future task to be solved. Nonetheless, it is clear that the quadrupole focus at the coupler of a TWA must be taken into account at an off-crest acceleration phase.

CONCLUSIONS

We experimentally evaluated the transverse beam dynamics model of a TWA proposed so far [1]. As a result, the beam orbit in the crest acceleration part was properly reproduced by this model. However, in the off-crest acceleration part, it was indicated that an additional focusing effect was necessary for the dynamics model. We found that a quadrupole field was excited in the coupler cell of a TWA by using a three-dimensional rf simulation. Furthermore, the sign of the quadrupole field in the input coupler is the same as that of the output coupler. This is in contrast with the monopole focusing effect, which shows the opposite sign between the input and output couplers. Therefore, the transverse dynamics model of a TWA was modified by the addition of a quadrupole effect, and the beam orbit in both the crest and off-crest acceleration parts was appropriately calculated by the new model. Thus, we conclude that the quadrupole focusing effect must be taken into account for the TWA operated at an off-crest acceleration phase.

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REFERENCES

[1] T. Hara, et al., Nucl. Instrum. Meth. A 624, 65 (2010).
[2] H. Matsumoto, et al., "C-band Choke Mode Accelerator Structure for the Linear Collider," Proceedings of EPAC'96, 489 (1996).
[3] H. Maesaka, et al., Nucl. Instrum. Meth. A 696, 66 (2012).
[4] J. Rosenzweig and L. Seraini, Phys. Rev. E 49, 1599 (1994).
[5] ANSYS, Inc., http://www.ansys.com
[6] C. Suzuki, et al., "Input Coupler Design for C-band Accelerating Structure," Proceedings of PAC'97, 536 (1997).

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