EMITTANCE GROWTH AND BEAM LOADING IN INTENSE ELECTRON BEAMS

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Abstract

In bunching intense electron beams, emittance growth due to two sources, rf field and space charge force, has been considered. The emittance growth in bunching intense beams has been simulated with the PARMELA code; the conditions for bunching with no excessive emittance growth have been explored. Beam loading effects, another problem in bunching high intensity electron beams, are also discussed.

Introduction

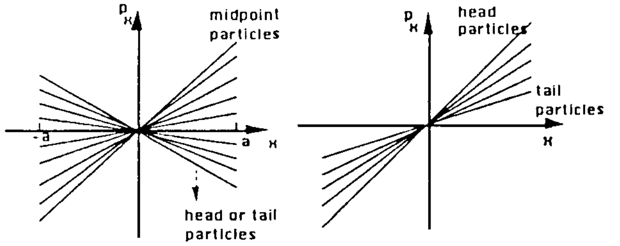
It is well-known that in electron linacs emittance grows mainly in the buncher. Several mechanisms for emittance growth have been proposed so far, and the contributions of them to the overall emittance may differ in particular bunching conditions and machines. Space charges and transverse rf fields are said to be two main sources of emittance growth in electron linacs. The emittance growth of a high intensity electron beam was estimated in the bunching condition for the KEK 2.5-GeV linac, a S-band linac(2856MHz), considering these effects. The multibunch beam loading effects on bunching was also considered. The bunching system consists of double prebuncher(PB1 and PB2) and a buncher[1], all of which are of traveling wave type.

Emittance Growth Due to RF Field

Emittance growth by the transverse component of the rf electric field is pointed out by many researchers[2,3]. We first estimated emittance growth in the prebuncher of the traveling wave type. The Lorentz force law gives the transverse force arising from the electric and magnetic components of the fundamental mode in an accelerator,

$$F_r = eE_0 \frac{r}{2}\frac{\omega}{c}\left(\frac{1-\beta_e\beta_w}{\beta_w}\right)\sin(\omega t-\beta z). \qquad (1)$$

It is clear from Eq. (1) that the particles having different phases receive different transverse forces, and, thus, gain different transverse momentum increases. First, let us calculate the emittance growth in the prebuncher, in case the bunch length reduces from one wavelength to a shorter length. Since the transverse force is proportional to the radius, we consider only the outermost particles which have the largest difference in the term $\sin(\omega t-\beta z)$. As in the prebuncher, where the particles are bunched together around a zero point (midpoint in this case) of the longitudinal field, the particles on the field zero receive outward transverse force and the opposite is true for the particles on the head or tail. Converting the force change to the momentum change, we get the emittance diagram as Fig. 1 for the particles on a transverse phase space. This figure shows that the initial particles moving parallel to the beam axis have different momentum gains according to their phases so that the representative points diverge on phase space. In this figure, the points on a tilted line represent the particles at the same longitudinal location (or rf phase) and different radii. The linearity corresponds to the proportionality of the transverse force to radius r. We can obtain emittance growth due to rf field by evaluating the area of two triangles. Using the values in the bunching of the KEK 2.5-GeV linac for the parameter of Eq. (1), we have an emittance growth of about 7 $\pi\cdot$mm$\cdot$mrad, which is a typical value gained from the simulation calculation with PARMELA. In a similar way, we can determine the emittance growth in the buncher, where the bunching proceeds on accelerating phases. Although the rf electric field in the buncher is very high, the emittance growth is small there since the bunch length is short. The calculated values under the typical bunching conditions are about 8 $\pi\cdot$mm$\cdot$mrad, a relatively small value compared to the emittance growth observed in the buncher.



(a) (b)

Fig. 1 Emittance growth due to the transverse components of the rf field. (a) bunching around a field zero (prebuncher), (b) bunching on accelerating phases (buncher).

Emittance Growth Due to Space Charge Force

Emittance growth also occurs by space charge force in high intensity electron beam. We can understand the emittance growth as follows (Fig. 2). When a bunch undergo a sudden bunching, the transverse force also increases suddenly due to space charge force and the emittance domain elongates in the transverse momentum axis direction. If the elongated emittance is not matched to the buncher, the emittance domain will rotate as a whole on phase space during propagation along the buncher. In this case, the difference in the particle energy and the rf effect discussed earlier make the rotation velocities of particles differ. The effect of the rf field is relatively small since the bunch length is short in the buncher compared to space charge force. In the next section we elaborate on this point.

Simulation on Bunching and Emittance Growth of High Current Electron Beams

We investigated the emittance growth in the buncher in bunching high intensity electron beams. In this calculation, we consider bunching a beam of 350 ps and 12 A. The magnetic field distribution is given by Helmholtz coils to maintain nearly the same radius of the beams.

Figure 3 shows the emittances at each cavity of the bunching system in the same bunching conditions except for the bunch input phase. In Condition I, the bunch is made to enter the buncher over the phase range between 10 and -50 degrees(a negative phase corresponds to acceleration), whereas in Condition II it enters the buncher over the phase range between -20 and -80 degrees. Therefore, the bunching occurs more suddenly in the former case. As a result, the final emittance of the Condition I is twice as large as that of the Condition II . In Condition I, the emittance growth occurs remarkably in the first four cavities of the buncher, whereas it is negligibly small in Condition II.

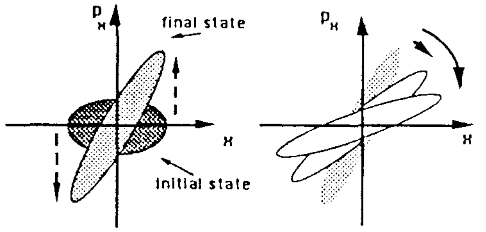


Fig. 2 Emittance growth by space charge force.

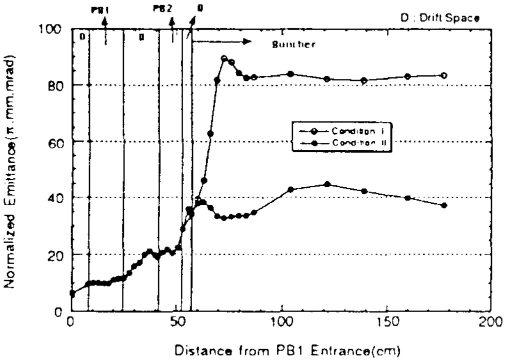


Fig. 3 Variation of the transverse emittances along the bunching system (current : 12 amperes).

To clarify this difference in emittance growth in the two cases, we plotted in Fig. 4 the variation of bunch lengths (FWHM) during bunching. We find that in Condition I, the bunching is almost completed in the first three cavities. At the third cavity, the bunch length reached 6 degrees (about 6 ps), and then the debunching starts. On the other hand, in Condition II, bunching proceeds relatively slowly, and the bunch shortens little by little over the first six cavities. The final bunch length of the Condition I is 11 degrees, compared to 7 degrees in Condition II. In sum, emittance growth is conspicuous when the bunching occurs rapidly in the first part of the buncher, where the beam energy is still low.

Next, we compared the transverse phase spaces to investigate the difference in the emittance growth. Figure 5 shows phase spaces for the two conditions at the third cavity of the buncher. As mentioned earlier, the bunch experiences strong bunching force in Condition I and the emittance domain elongates in the vertical axis with rapid bunching. The domain grows large by the process mentioned in Fig. 2, whereas no noticeable change in emittance domain is observed in Condition II between before and after the bunching.

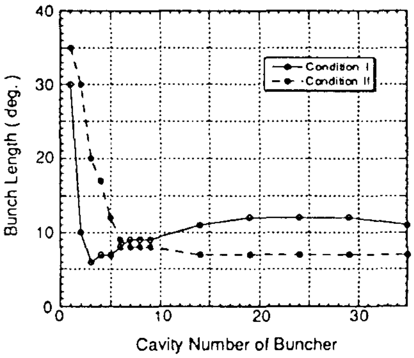


Fig. 4 Change in the bunch lengths in the buncher with bunching for Condition I and Condition II

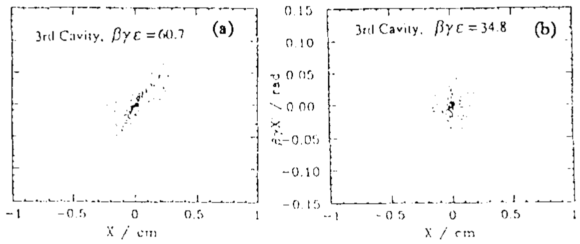


Fig. 5 Comparison of phase spaces for the two conditions at the third cavity of the buncher(normalized emittances are also shown), (a) Condition I, and (b) Condition II.

Beam Loading Effects of High Intensity Electron Beam in the Buncher

We estimated the multibunch beam loading in the buncher for a beam of pulse width 15 ns under the following simplifying assumptions. First, the bunch is assumed to pass through each cavity with the same length, i.e., the mean length in the cavity. Second, the induced power propagates downstream at the group velocity, this flow is ignored since the group velocity is much lower than the velocity of the bunches. Furthermore, the wall loss is ignored. Under these assumptions, we have the voltage induced in a cavity by a bunch of length t_b in rectangular shape[4].

$$\tilde{V} = \frac{\sin(\omega_0 t_b/2)}{\omega_0 t_b/2} V_0 e^{j\omega_0 t}, \qquad (2)$$

where $V_0 e^{j\omega_0 t}$ is the voltage induced by a point charge q. Since the coefficient, $\sin(\omega_0 t_b/2)/(\omega_0 t_b/2)$, is a very slowly varying function in the range of $\omega_0 t_b/2 << \pi/2$, the differences of beam loading due to the bunch length can be disregarded in practical purposes, which allows the assumption that the beam loading by a bunch is constant for all the cavities of the buncher.

In the following, we will compute the multibunch beam loading in transient state. In the calculation, since the beam pulse length (15 ns) is very short compared with the filling time (about 340 ns), a transient beam loading is enough to consider. A point charge q traversing a cavity with loss parameter k induces a voltage[4]

$$V_0 = 2kq = 2q\frac{\omega}{4}\frac{R_a}{Q} = \frac{q\omega}{2}\frac{R_a}{Q}, \qquad (3)$$

where R_a is the shunt impedance of the cavity, and Q the quality factor. We calculated the beam loading voltage for the buncher of the KEK 2.5-GeV linac. Although R_a increases slowly along the z axis since the buncher is a constant gradient type, we regard it as constant because of its sufficiently small variation. Substituting the corresponding values[1,5] in the parameters of Eq. (3), we obtain the induced voltage of 4.5 kV/cavity, or 128 kV/m by one bunch.

Since a beam dynamics code including the multibunch beam loading in the buncher is not available at present, we first compute the multibunch beam loading in an analytical way.

To begin, in order to compute the beam loading seen by rear bunches in a cavity, we consider the phasor diagram in Fig. 6. The angle ϕ_n is the angle between the n-th bunch and the crest of the rf voltage wave. The phasor E_{b1} indicates the induced voltage by the first bunch, 128 kV/m. The second bunch will see the superposed voltage of E_{rf} and E_{b1}. From the above assumptions, the value E_{bn} is the same for all n. An inspection will give the phase and electric field amplitude for the n-th bunch in terms of the amplitude of the first bunch, E_{01} as in Fig. 6.

To estimate the beam loading effect for the n-th bunch, we used the above calculated phase and amplitude as input data of PARMELA for the n-th bunch.

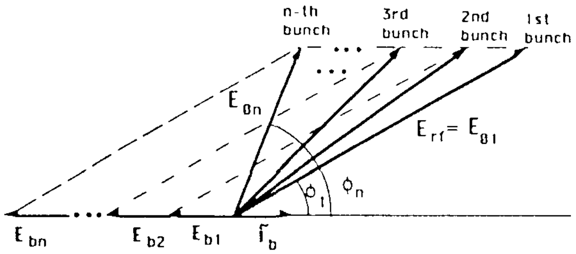


Fig. 6 Induced beam loading voltage at a cavity in the buncher. The induced voltages accumulate continuously and a bunch in the pulse sees the voltage obtained by superposing the external rf field, E_{rf} and loading induced by all the preceding bunches.

$$\phi_n = \arctan\left(\frac{E_{01}\sin\phi_1}{E_{01}\cos\phi_1 - (n-1)E_{b1}}\right),$$

$$E_{0n} = \left\{\left(E_{01}\sin\phi_1\right)^2 + \left(E_{01}\cos\phi_1 - (n-1)E_{b1}\right)^2\right\}^{1/2}.$$

We calculated the amplitude and phase affected by the beam loading of prior bunches when a beam of 12 amperes (4.2 nC/bunch) and 15 ns is bunched in the 15 MV/m of electric field in the KEK 2.5-GeV linac. The calculation shows that the phase shift for the last bunch in comparison with the first one is about 20 degrees in the direction of lower accelerating phase and the electric field was 15% reduced by the beam loading. The condition for the first bunch is the same as the Condition II in the previous section.

The result shows that the emittance of the last bunch is about 25% greater than that of the first one. This is a direct result of the phase shift for the last bunch since the phase shift causes a rapid bunching by a large energy difference caused in the bunch, which is consistent with the previous result on the emittance growth. In addition to the emittance growth, two additional effects are recognized in the last bunch(Fig. 7). The asymptotic phase of the last bunch is shifted by 15 degrees compared to the first bunch, and the bunch length is 4 ps longer than the first bunch, of which the length is 6 ps. These two effects are thought to be caused by the decrease in the electric field amplitude due to the beam loading. Since the change of the asymptotic phases means the elongation of the intervals between bunches in the rear bunches, it will deteriorate the energy dispersion from bunch to bunch in the multibunch beam in subsequent regular accelerators.

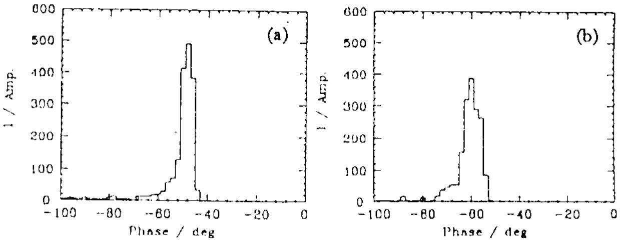


Fig. 7 Longitudinal phase space and bunch shape of (a) the first bunch and (b)the last bunch at the last cavity of the buncher.

Summary

The emittance growth of high intensity electron beam was estimated in the bunching condition of the KEK 2.5-GeV linac considering the rf effects and space charge efects. The contribution by rf to the total emittance growth was very small. Emittance growth was large when the bunching occurred rapidly in the buncher. This is believed to be the result of the space charge force. The multibunch beam loading caused bunch lengthening and the shift of the asymptotic phases of the rear bunches, and emittance growth as well.

References

[1] S. Ohsawa, et al., Proc. 1992 Linear Accel. Conf., 91 (1992)
[2] Kwang-Je Kim, Nucl. Instrum. Meth., A275, pp. 201 (1989)
[3] R. H. Miller, C. H. Kim, F. B. Selph, Conf. European Part. Accel. Conf., pp. 863 (1988)
[4] P. B. Wilson, High energy electron linacs, AIP Conf. Proc. 87 (AIP, New York), pp. 450 (1982)
[5] S. Ohsawa, private communication.