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Simulation Study of Beam Bunching in the New Pre-Injector of the KEK 2.5-GeV Linac

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Abstract

We have performed a simulation study concerning beam bunching in the new pre-injector of the KEK 2.5-GeV linac comprising double prebunchers and a buncher. The dependence of the bunching performance upon the rf powers and the phases of the prebunchers is discussed. We obtained an optimum bunch length of 4 ps based on the simulation.

I. INTRODUCTION

The pre-injector of the KEK 2.5-GeV linac was upgraded during the summer of 1992 [1]. The bunching system was improved in order to accelerate the more intense electron beams required for producing positrons for the KEK B-factory [2], which is under consideration as a future KEK project. A short bunch is essential for the injection efficiency to the B-factory ring, since the bunch length of the electrons determines that of the positrons and sets the limit on the narrowness of the energy spectrum. In addition, the emittance degradation due to the transverse wake-field is larger for a longer bunch. To achieve a good bunching performance, we have adopted a system comprising double prebunchers and a buncher. This system was designed to be flexible; thus, the rf input power and the relative rf accelerating phase of each buncher are independently tunable for optimum bunching. The parameters of the system are adjusted according to the change in the beam conditions, such as the currents and pulse length. The dependence of the bunch length upon the relative phases and the rf input powers of the prebunchers was studied using a beam-dynamics simulation code.

II. BUNCHING SYSTEM

In bunching an intense beam, it is important to minimize the effect of debunching due to any space-charge forces. We thus adopted a system of double prebunchers and a buncher. The first prebuncher (PB1) provides a d-c beam from a gun with a velocity modulation; the beam is slightly bunched in the drift space to the second prebuncher (PB2). The rf phase for PB2 is adjusted so that the electrons enter PB2 in accelerating phase, causing a further bunching as well as acceleration. Since beam debunching is significant at low energy, it is desirable to accelerate the electrons during the earlier stage of bunching. The acceleration of electrons by PB2 before entering the buncher is effective for improving the bunching performance. The electrons are finally bunched in the strong accelerating field of the buncher.

A schematic diagram of the system is shown in Figure 1. The parameters of the bunchers are summarized in Table 1. All three bunchers are traveling-wave structures operating in the $2\pi/3$ mode at 2856 MHz. An array of Helmholtz coils encompasses the bunchers. They produce a uniform solenoidal focusing field of 1.0 kG. A new high-power attenuator-and-phase-shifter system is used for independently adjusting the rf input power and the accelerating rf phase [3]. This flexibility of the bunching system is expected to enhance the capability of the parameter tuning.

Table 1
Bunching system design values

Prebuncher 1 (PB1)	
maximum field	0.4 MV/m
available input power	0.1 MW
cavity number	7
cavity size D	24.318 mm
Prebuncher 2 (PB2)	
maximum field	2.0 MV/m
available input power	2.3 MW
cavity number	5
cavity size D	24.318 mm
Buncher	
maximum field	15 MV/m
available input power	13 MW
number of cavities	
buncher section	6
normal section	29
cavity size D	27.01 ~ 34.99 mm
Focusing magnetic field	
Helmholtz coils	1.0 kG

We have estimated the performance of the system in a search for the optimum values for these operation parameters using the simulation code PARMELA.

III. SIMULATION

The PARMELA code is widely used for designing the bunching systems of electron linear accelerators [4]. In this code, an electron beam is represented by a few hundred

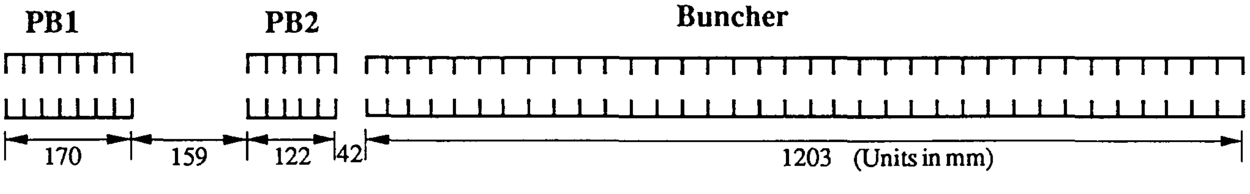

Figure. 1 Layout of the first and second prebuncher and the buncher

(~300 in our calculations) macroparticles. They are traced during consecutive finite time-steps under the influence of the accelerating electric fields, the focusing magnetic fields and the space-charge forces. The effects due to the wake-field in the cavities were not taken into account. As an initial condition, these macroparticles were assumed to be randomly distributed within the specified volume in 4-dimensional transverse phase space. The initial transverse r.m.s. emittance was taken to be 7π mm.mrad. In the longitudinal direction, they have a uniform distribution within the range corresponding to one wavelength $\beta\lambda$ (= 73.5 mm) of the 2856 MHz rf acceleration, where β=v/c. Their initial energies were 200 keV. All of the calculations were carried out for a beam current of 4 A.

To estimate the bunching performance of our double prebuncher system, we studied the dependence of the bunch lengths upon the rf parameters of PB1 and PB2. The shapes of the bunches are dependent upon these parameters. Under certain conditions, bunches have very irregular forms, as shown in Figure 4(a). To discuss the bunch lengths of such irregular bunches, FWHM's or r.m.s. widths are not suitable. Instead, we used a fraction of the particles which lie within the rf phase width of 4 degrees around the peak of the distribution (Bunch Core). We chose this criterion because the optimum bunch width obtained by the calculations was about 4 degrees. This reflects well not only the sharpness of the bunch shapes, but also the extent of the tail or sub-peaks, regardless of the forms of the bunches. We, therefore, use this criterion as an index for evaluating the bunching performance in the following discussion.

In studying the dependence of the bunching performance upon the rf parameters, we took high and low field cases of PB1. The dependence upon the rf field and the input phase of PB2 was mainly studied with those of the buncher fixed. Table 2 gives the range by which the rf fields varied in the calculations.

Table 2
Range of the rf fields

PB1	0.15, 0.40 MV/m
PB2	0.1 ~ 2.5 MV/m
Buncher	15 MV/m

IV. RESULTS & DISCUSSION

The bunching performance is dependent not only on the electric field of the prebunchers, but also on their relative phases. The effect of their electric fields was studied first. The relative rf phase of PB2 to that of PB1 was fixed, so that the incident phase at PB2 was 30 degrees for a reference particle which was at the zero phase in PB1. The incident phase at the buncher was also fixed to 50 degrees in the case that the field of PB2 was 2.0 MV/m. Figure 2 shows the dependence of the bunching performance upon the electric field of PB2. It was evaluated based on the index defined in the previous section.

It can be shown that a better performance is obtained for the weaker field (0.15 MV/m) of PB1 over the entire range in Figure 2. The optimum value of the electric field of PB2 was 2.0 MV/m for both cases.

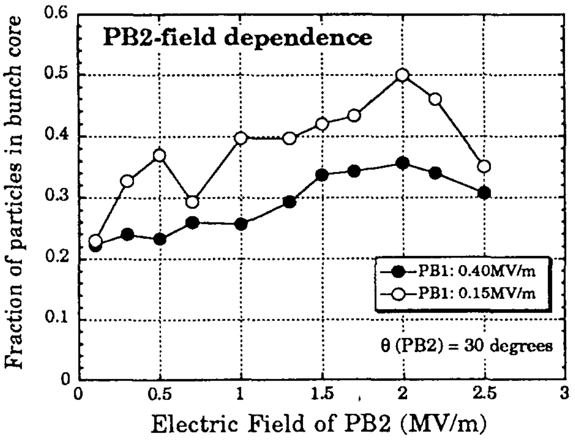

Figure 2. Dependence of the bunching performance upon the electric field of PB2.

Concerning the bunching performance upon the phase of PB2, we studied cases for PB2 fields of 1.0 and 2.0 MV/m (Figure 3). The relative phase of the buncher to that of PB1 was not changed.

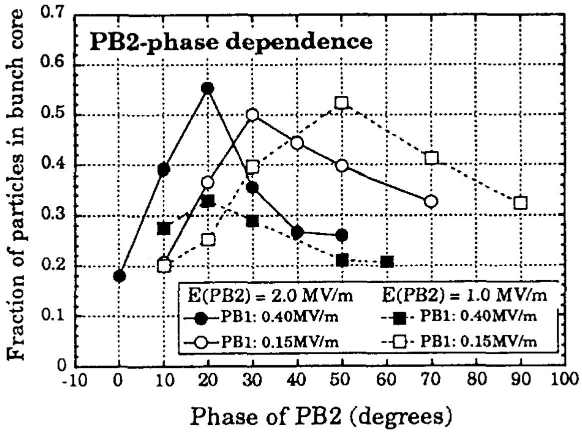

Figure 3. Dependence of the bunching performance upon the rf phase of PB2.

For the weaker field (0.15 MV/m) of PB1, good performances were obtained for a wide range of phases of PB2. The range was narrower for the stronger field (0.40 MV/m) of PB1, and two-peak structures of the bunches were observed for conditions slightly away from the optimum value, as shown in Figure 4 (a). Similar structures were also observed in the experiments, as shown in Figure 4 (b). The structure is believed to be caused by over-bunching due to the excessive field of PB1.

With the optimum condition obtained for the stronger field of PB1, the two peaks are expected to coalesce. The calculated trajectories for this case are given in Figure 5. It shows that the two sub-bunches, formed by over-bunching, coalesce in such a particular phase relation that the preceding sub-bunch is decelerated, while the subsequent sub-bunch is accelerated in the rf field of PB2. The discontinuity of the trajectories shown in the figure is due to the fact that the positions of the particles are expressed with reference to the rf phase of each buncher. Though this condition gives good performance, the tolerance of the relative phase of PB2 is small, as shown in Figure 3.

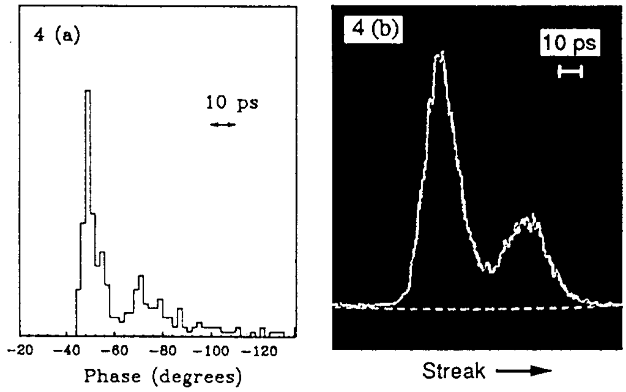

Figure 4. Bunches with a two-peak structure by calculation (a) and measurement (b) [5].

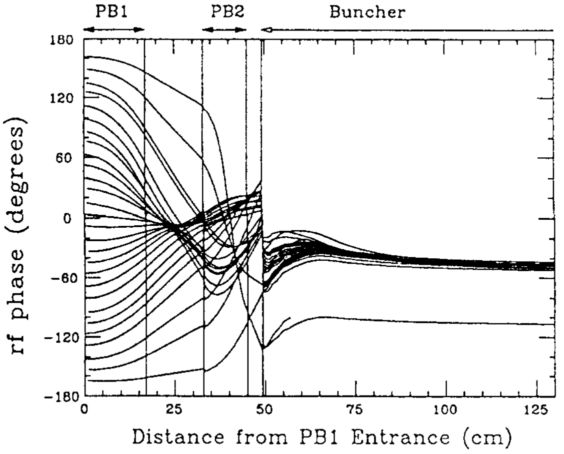

Figure 5. Typical trajectories for the optimum condition with a field of 0.4 MV/m for PB1.

For the optimum condition for weaker field (0.15 MV/m) of PB1, the calculated trajectories are shown in Figure 6. This optimum bunching results from moderate bunching by PB1 and the additional bunching by PB2 and the buncher. The bunch shape under this condition is shown in Figure 7. The FWHM bunch width is estimated to be about 4 degrees, which corresponds to a time duration of 4 ps.

V. SUMMARY

We have studied the bunching performances of our new bunching system with the simulation code PARMELA. A bunch length of 4 ps was obtained as a preliminary optimum value. Further extensive optimization of the parameters with the simulation will be performed. The effects due to a longitudinal wake-field will be included there. Experimental studies measuring the bunch length with the optical transition radiation monitor [5] will also be undertaken.

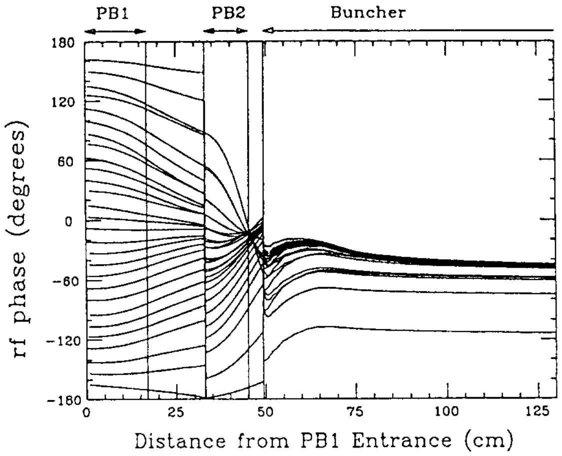

Figure 6. Typical trajectories for the optimum condition with a field of 0.15 MV/m for PB1.

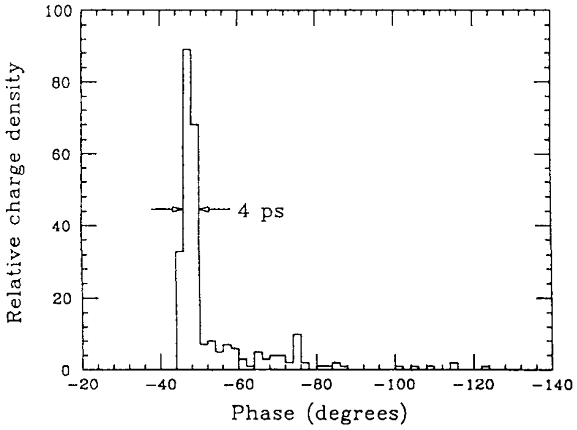

Figure 7. Bunch shape calculated for the optimum condition with a field of 0.15 MV/m for PB1.

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