Compensation of Bunch Position Shift Using Sub-RF Cavity in a Damping Ring

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Abstract

In the damping rings of future linear colliders, bunches will be filled along the ring in a bunch-train configuration, where spacing between trains is much larger than bunch-to-bunch spacing in a train. Because of this configuration, beam loading in RF cavities will cause the shift of bunches from their nominal longitudinal positions. The shift can be compensated with an active or a passive RF cavity whose resonance frequency is well controlled. By tracking simulations, the method is demonstrated for ATF damping ring at KEK.

I. INTRODUCTION

In order to achieve high luminosity, a train of many bunches with narrow spacing is accelerated in a long RF pulse . In the damping rings for this type of operation, beams should have bunch-train configurations. Beams in the ring will consist of some trains which contain many bunches with narrow spacing. Spacing between trains in a ring should be longer than rise and fall time of kicker magnets for injection and extraction and will be much longer than spacing of bunches in a train. In the present design of JLC(Japan Linear Collider), spacing between bunches in a train is less than 6 nsec and spacing between trains is more than 60 nsec.

Bunches in this configuration induce transient beam loading in RF cavities varying from bunch to bunch in a train; a bunch in tail of a train feels higher wake field than a bunch in head of a train. This non uniformity causes shift of bunch positions according to where the bunches are in a train. Without any cure, the maximum amount of shift from nominal positions can be more than bunch length resulting in a significant deterioration of the quality of the multibunch beam.

In order to compensate different beam loading from bunch to bunch in the main RF cavities, sub-RF system is proposed here.

The effect of the system is demonstrated by tracking simulations for the ATF(Accelerator Test Facility at KEK) damping ring. Longitudinal bunch motions were simulated taking account the generator induced voltage, wakefield of the accelerating mode and wakefield of some higher order modes. Each bunch was assumed to be a point charge. Used parameters of the ring are as follows.

Beam energy	1.54 GeV
Revolution frequency	2.16 MHz
RF frequency	714 MHz
Maximum beam current	0.6A
Radiation loss	0.20MeV/turn
Momentum compaction α	0.003
Damping partition number	1.78
RF cavity : Total voltage	1.2 MV
Shunt impedance	14.4 MΩ
Unloaded Q	22000
Coupling	2.34

Various scheme of bunch configurations (number of trains, number of bunches in a train and charge of a bunch) will be tested in the ATF within the maximum total current of 0.6A. In this paper, two extreme cases were examined as examples:

Case (a). 5 trains/ring, 20 bunches/train and 2×10^{10} e/bunch
Case (b). 3 trains/ring, 68 bunches/train and 1×10^{10} e/bunch

II. EQUILIBRIUM POSITION SHIFT

Accelerating field in RF cavities will be controlled by feedback loop to keep the field strength and phase constant. Because speed of the feed back will be much slower than the transient time of a train, field induced by non uniformly filled bunches can not be compensated. This will cause time dependent modulation of the amplitude and phase of accelerating field within a train.

Fig. 1 shows change of amplitude and phase of total cavity voltage vs. time which are calculated by tracking simulation for the case (a). The trajectory of the voltage on complex plane can be seen in Fig. 2 where reference phase is the phase of nominal bunch position. During passage of a bunch train, bunches induce voltage of opposite direction to themselves. Between trains, the field decays and rotates according to the Q-value and frequency detuning of the cavities.

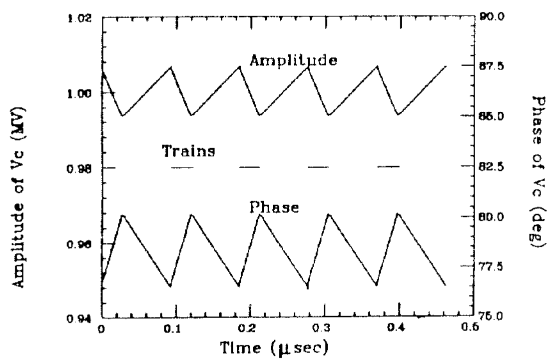

Fig. 1, Amplitude and phase of cavity voltage with non uniform bunch population.

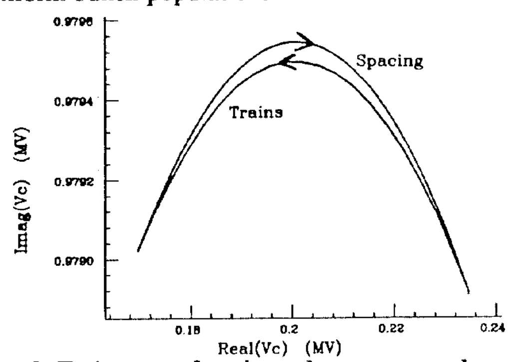

Fig. 2, Trajectory of cavity voltage on complex plane.

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Because all bunches have the equal revolution time, the energy must be equal and radiation loss of all bunches along the ring should have the same value. This means all bunches should gain the same voltage at the RF cavities. To be accelerated by the same amount from the field of different amplitude and phase, bunches will change their timing of passage at the cavities or the equilibrium position of bunches will shift from their nominal positions. Fig. 3 shows time delay from nominal positions of 1st, 10th and 20th bunches in a train which are calculated by tracking simulations for the case (a). The horizontal axis shows number of turns along the ring. The equilibrium position of the head bunch is delayed and tail bunch is advanced from the nominal positions. Initial condition was that all bunches have the same longitudinal position error of 10 psec. Fig. 4 (a) and (b) show the equilibrium positions of bunches vs. bunch number in a train for the case (a) and (b), respectively. Bunch number 1 means the head bunch in a train and the last number means the tail of a train. The values of the shift are almost linear to the bunch number. Nonlinearity of the first bunch is caused by the wakefield of the higher order mode.

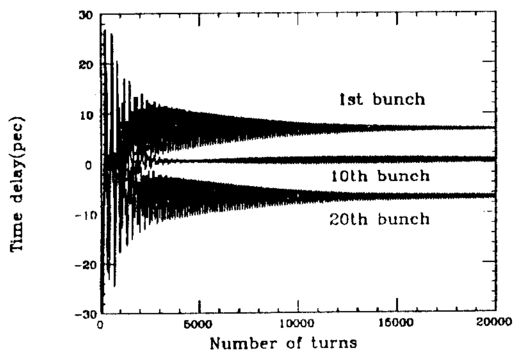

Fig. 3, Time delay from nominal positions of 1st, 10th and 20th bunches in a train versus number of revolution.

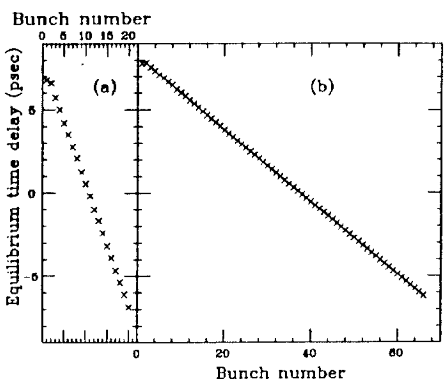

Fig. 4, Equilibrium positions of bunches vs. bunch number for case (a) and case (b).

The maximum values of the shift in both cases are comparable of the bunch length of the order of 10 psec. After extracted from the ring, the position difference means different RF phases along the main linac of the linear collider. The resulting significant energy difference may easily deteriorate the emittance of multibunch beam through bunch compressor, main linac and final focus region.

III. COMPENSATION BY ACTIVE SUB-RF SYSTEM

To correct the shift of the bunch positions, sub-RF system is proposed. RF field with frequency of

$$f_{sub} = f_{RF} - N_t f_{rev}$$

can compensate the difference of the field of the main RF, where f_{RF} is the frequency of the main RF, f_{rev} the revolution frequency and N_t the number of trains. Adjusting the phase of the sub-RF field so that the voltage is zero at the nominal timing of the passage of the center bunch in a train, bunches in head of a train will be decelerated and bunches in tail of a train will accelerated. If length of a bunch-train is short enough compared with the bunch spacing, as in the case (a), the compensation can be almost linear. But if the length is not short, as in the case (b), the nonlinearity of the compensation field may be important.

As is shown in Fig. 2, required strength of compensation field is several tens of kilovolts and can be obtained by introducing one cavity (sub-RF cavity).

The total voltage is vector sum of generator (external power source) induced voltage and beam induced voltage. Here, shunt impedance, unloaded Q and loaded Q of the sub-RF cavity are assumed to be 2MΩ, 20000 and 10000, respectively. Amplitude and phase of the total voltage is assumed to be fixed by controlling cavity tuning and RF input. In the case of (a), in order to obtain total voltage of 40 kV and the phase of 90 degree respect to the nominal phase of the center bunches in trains, detuning angle (detuning from sub-RF frequency f_{sub}) is -86.1^{o} and required power is 0.8 kW.

Fig. 5 shows time delay from nominal positions of 1st, 10th and 20th bunches in a train with sub-RF, which are calculated by tracking simulations for the case (a). This can be compared with the result without compensation in Fig. 3. Fig. 6(a) shows the equilibrium positions of bunches vs. bunch number in a train for the case (a) with sub-RF whose voltages are set to be 30 kV, 40 kV, 50kV and 60 kV. Fig. 6(b) shows the equilibrium positions of bunches vs. bunch number in a train for the case (b) with sub-RF voltages are set to be 20 kV, 30 kV, 40kV and 50 kV. This shows voltage of about 30 ~ 40 kV is optimum. In the case (a), the residual shift is much smaller than the bunch length (about 5 mm in r.m.s.). In the case (b), the residual is several percent of the bunch length in r.m.s.

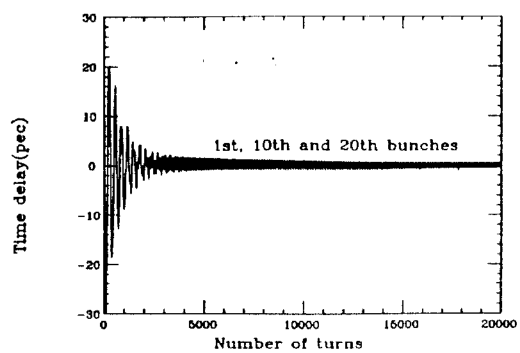

Fig. 5, Time delay from nominal positions, 1st, 10th and 20th bunches in a train for case (a) with active sub-RF.

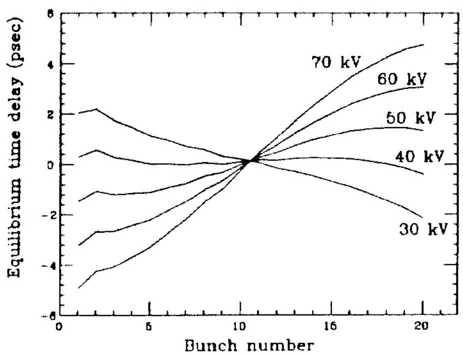

Fig. 6(a) Equilibrium positions of bunches vs. bunch number for case (a) with active sub-RF.

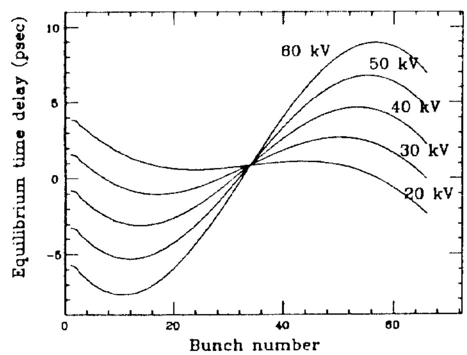

Fig. 6(b) Equilibrium positions of bunches vs. bunch number for case (b) with active sub-RF.

IV.COMPENSATION BY PASSIVE SUB-RF SYSTEM

If detuning angle (φ) of sub-RF cavity is near -90°, the phase of beam induced voltage is near by 90° with respect to the center beam and the generator induced voltage is very small ($\cos\varphi$ of the total voltage). Without generator power, the voltage in the sub-RF cavity is only beam induced voltage. It means that the compensation will possible without input power. For a passive RF cavity, only resonance frequency can be controlled in operations in order to obtain appropriate compensation.

With the same parameters as in section III but without input power, tracking simulations were performed with some cases of detuning of the cavity. Fig. 7 shows time delay from nominal positions of 1st, 10th and 20th bunches in a train with passive sub-RF for the case (a) where cavity detuning angle is -86.0° or detuning from fsub is -500 kHz. Fig. 8(a) and (b) show the equilibrium positions of bunches vs. bunch number in a train with passive sub-RF with several detuning frequencies. These figures show that a frequency controlled passive sub-RF cavity can be used for the compensation. With appropriate detuning, residual shift is as small as that with active sub-RF compensation in each case.

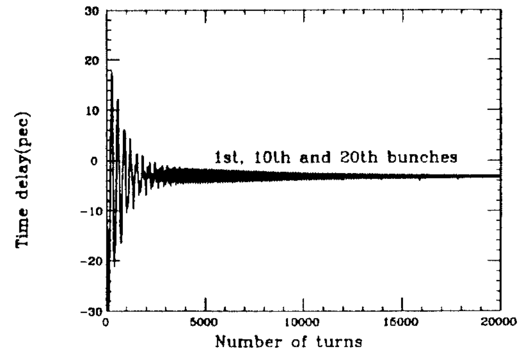

Fig. 7, Time delay from nominal positions, 1st, 10th and 20th bunches in a train for case (a) with passive sub-RF.

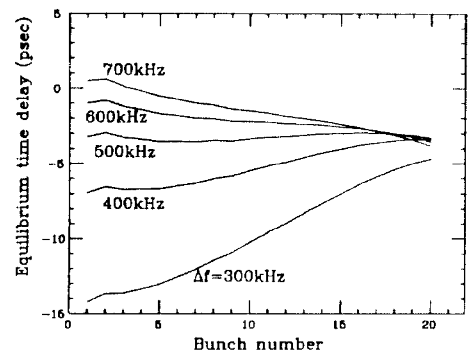

Fig. 8(a) Equilibrium positions of bunches vs. bunch number for case (a) with passive sub-RF.

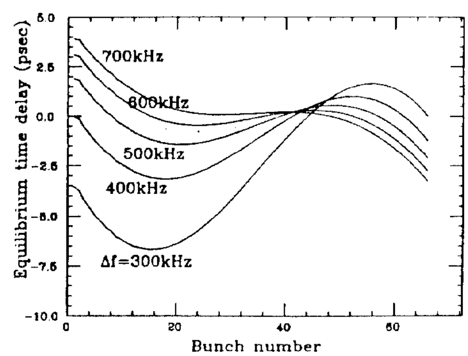

Fig. 8(b) Equilibrium positions of bunches vs. bunch number for case (b) with passive sub-RF.

V. SUMMARY AND DISCUSSION

It was found that equilibrium position shift in damping rings for future linear colliders with bunch-train configuration can be compensated by active or passive sub-RF system.

As the case (b), if length of a train is longer than spacing between trains, residual shift may be significant. If necessary, adding higher order sub-RF with frequency of

$f_{RF} - nN_t f_{rev}$ (n=2,3, ...),

this residual shift will be compensated.