IEEE Transactions on Nuclear Science, Vol. NS-28, No. 3, June 1981

RF PHASE SHAKE AND COUNTERPHASING AT PHASE TRANSITION

Y. Mizumachi and K. Muto

KEK, National Laboratory for High Energy Physics
Oho, Tsukuba, Ibaraki 305, Japan

Summary

The KEK 12-GeV PS suffers from noticeable beam loss just after the phase transition when the beam intensity exceeds 2×10^{12} ppp. Longitudinal instability has been suspected to be the cause of the loss. (We have observed microwave disturbance in the beam as well as very turbulent coherent oscillations and subsequent large emittance blow-up.) Artificial bunch dilution before the transition has been proposed to moderate these dangerous instabilities and to prevent phase transition beam loss. Two RF manipulations have been tested; one is RF phase shake and the other is RF cavity counterphasing. The "phase shake" modulates the RF phase and the "counterphasing" lowers the net accelerating voltage. The phase shake has remarkably reduced the beam loss when the phase modulation frequency is much higher than the synchrotron frequency. Counterphasing has exhibited similar effect. Both operations can decrease the beam loss when they produce bunch flattening before the transition crossing. These methods contributed to the KEK 12-GeV PS record intensity 4×10^{12} ppp (4.4×10^{11} p/bunch).

1. Beam behaviors at the phase transition

The beam loss at the transition energy (5.4 GeV) has long been a problem of the KEK 12-GeV Main Ring synchrotron. In early operations large loss took place even when the beam intensity was far below 1×10^{12} ppp. The loss at such low intensity has almost been eliminated by the improvements of beam feedback circuits.[1] However, since the beam intensity has exceeded 2×10^{12} ppp (design value), transition loss has again become significant. Though the loss has been reduced by the addition of the fourth RF cavity, it still remains noticeable.

Typical operation of 12-GeV PS is shown in Fig. 1. Bunches are injected from the 500-MeV Booster with 50 ms interval. Sharp beam loss occurs at the transition energy. As in usual AG synchrotrons, bunch height increases very steeply toward the transition and it suddenly decreases immediately after the transition.

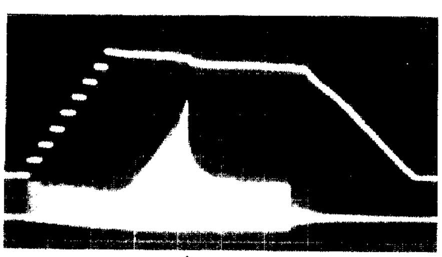

Fig. 1 Operation of 12-GeV PS. (200 ms/div)

Close-up view of the transition is shown in Fig. 2. In this figure we can see simultaneous envelopes of individual bunches. Quadrupole oscillations are remarkable both before and after the transition. Interesting fact is that the individual quadrupole oscillations have the same phase after the transition while they have independent phases before the transition.

Top trace in Fig. 2 shows that the sharp beam loss takes place within about one synchrotron oscillation period. In the mountain view display of bunches just after the transition (Fig. 3), we observe that some part of each bunch branches off leftwards. This means that some part of the beam goes out of RF bucket and will be lost. In accordance with the observation in Fig. 2, these branches appear only in about one synchrotron oscillation period.

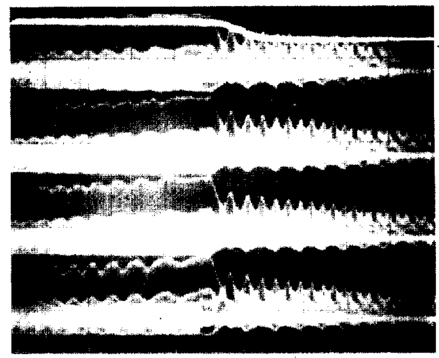

Fig. 2 Beam signals around the phase transition. Individual bunches are separated in the display. (Only four bunches are shown.)

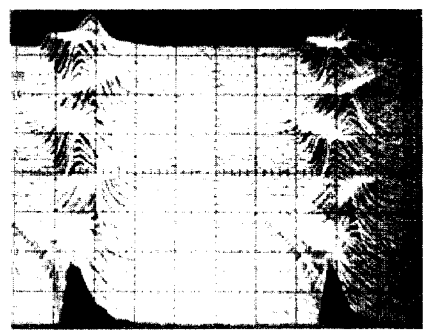

Fig. 3

Beam spill from the RF bucket just after the phase jump. (20 ns/div, 252 revolutions/trace)

Further close-up view (Fig. 4) shows us that the spilt branch has very high frequency structure around 800 MHz. This structure becomes evident in the bunches after the phase jump earlier than the appearance of quadrupole oscillation. At the transition, local value of $(\Delta p/p)^2/i$ is very large but η is nearly zero. Therefore, it seems reasonable to deduce from Keil-Schnell criterion that the 800 MHz structure is due to the microwave instability in the bunch though the beam condition is quite different from the case where Boussard first found the microwave instability.[2]

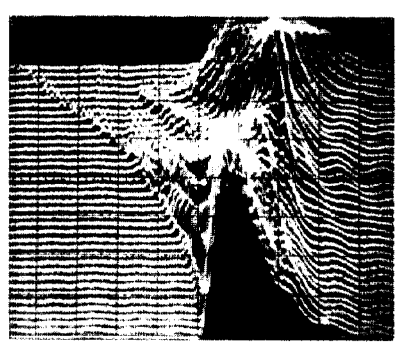

Fig. 4

Microwave disturbance in the bunches after the phase jump. (10 ns/div, 242 revolutions/trace)

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2. Phase shake

If the microwave instability plays the dominant role in the transition beam loss, two measures are conceivable to avoid the instability; one is to eliminate high impedance beam equipments in the 12-GeV ring and the other is to dilute the phase space density of the beam before the transition crossing. First approach will need a lot of works to identify the harmful equipment concerned. Second one can be pursued more easily and with minimum interference to the machine operations.

Sinusoidal phase modulation of the accelerating RF voltage (phase shake) was first tested with the scheme shown in Fig. 5 to get possible emittance growth. When the shaking voltage is applied to the phase shifter-A (PS-A), characteristic responses appear in the radial position signal (*dr*) according as the frequency range of shaking. When the shaking frequency *fm* is much lower than the synchrotron frequency *fs* radial feedback loop works to cancel out the shaking at PS-A.

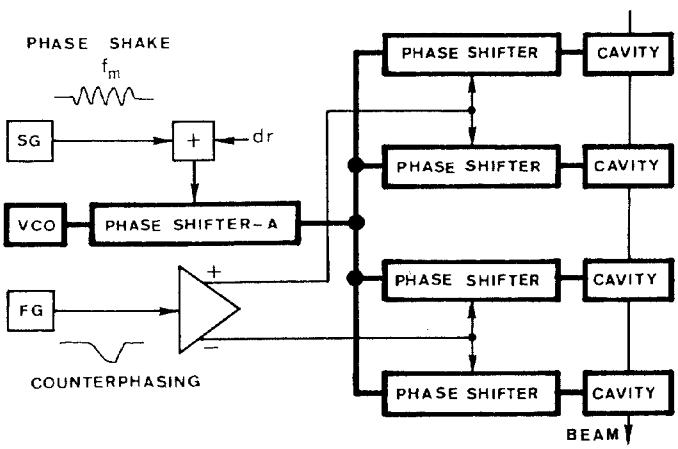


Fig. 5 Scheme of phase shake and counterphasing at the phase transition.

Therefore, we have the radial shift which has the same frequency but the inverse phase as the shaking voltage. In this case, beam pulse (not each particle in the beam) stays on the same phase of RF voltage. As *fm* increases and comes near to *fs*, *dr* response decreases and shows phase lags. When *fm* is close to *fs*, resonance occurs and beam is destroyed even with very small shaking amplitude. Weaker resonance occurs and beam becomes unstable with shaking around 2*fs*. When *fm* is much higher than *fs*, radial loop cannot follow the phase shake at all and the voltage-kick on the beam is influenced by the shake. In this last case, we observe negative (inward) shift of radial position when the shaking amplitude is large. This negative shift is due to the non-linearity of sinusoidal voltage as illustrated in Fig. 6.

Though various shaking conditions were tested, no effective emittance growth was obtained. For example, shaking at the frequency 2*fs* was expected to be very effective for that purpose but this did not work well and easily caused a significant beam loss. This is probably because the RF bucket is not so large enough as to allow such a process.

After many trials it was found that the phase shake just at the phase transition is very effective to reduce the transition loss. The loss decreases when the following conditions are satisfied;

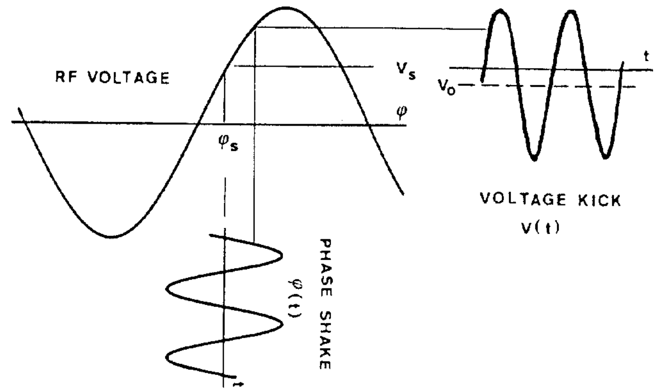
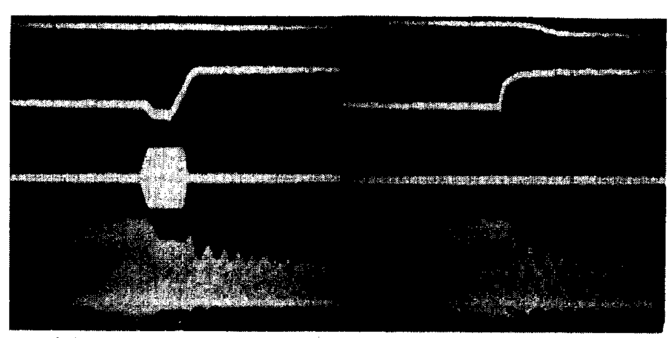


Fig. 6 Instantaneous values of beam phase angle $\phi(t)$ and RF voltage kick $V(t)$ during the fast phase shake. If the shaking amplitude is large, average accelerating voltage *Vo* is lower than *Vs* (voltage at the synchronous phase ϕs) as long as $\sin \phi s > 0$. Hence radial position shifts inward.

(1) frequency condition: *fm* is much higher than *fs* around the phase transition. (typically $fm \approx 10$ kHz),
(2) timing condition: the shaking is turned on some time (several ms to several tens of ms) before the phase transition and turned off just at the timing of phase jump,
(3) amplitude condition: the shaking amplitude is large enough to yield negative radial shift.

A successful phase shake operation is shown in Fig. 7(a) in comparison with the case without phase shake (Fig. 7(b)). The bunch height is suppressed by the phase shake just before the phase jump. However, this bunch flattening does not mean the emittance growth; if we turn off the phase shake a little before the phase jump, bunch envelope recovers the height as when there is no shaking operations and then the beam loss appears. Therefore, we can conclude that the large amplitude phase shake causes only bunch flattening by the effective voltage reduction which is confirmed by the inward movement of *dr* signal.

Anyway, it is essential to meet the phase jump with flattened bunch shapes. At the same time, we must stop the shaking right at the phase jump because large phase shaking becomes very dangerous operation after the emittance blow-up has occurred. These explain why we need the timing condition (2).



(a) phase shake ON (b) phase shake OFF

Fig. 7 Performance of phase shake at the phase transition. (10 ms/div)
Traces are: 1. proton number (5×10^{11}/div)
2. radial position signal
3. phase shake voltage (~80°/div)
4. bunch signal

3. Counterphasing

If the bunch flattening is the essential point of phase shake on the transition beam loss, we can expect a similar effect by just lowering the accelerating RF voltage. Net accelerating voltage is lowered by the cavity counterphasing scheme shown in Fig. 5. As is shown in Fig. 8, bunch flattening can again eliminate the transition loss. We can obtain similar effects

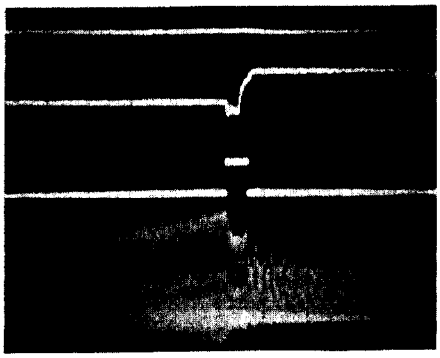


Fig. 8 Performance of counterphasing at the phase transition. (20 ms/div)
Traces are: 1. proton number (5×10^{11}/div)
2. dr signal
3. counterphasing voltage
4. bunch signal

with various counterphasing voltage patterns. Another example is shown in Fig. 9 where the reduction of net accelerating voltage is displayed by the synthesis of four cavity voltages. A step which appears in the RF voltage envelope just at the timing of phase jump shows the accompanying beam loading jump. Fig. 10 shows the actual bunch flattening by counterphasing.

Fig. 11(a) shows the bunch shapes 2 ms after the phase jump when the counterphasing has been applied. Coherent quadrupole oscillation has not started yet. Fig. 11(b) shows the corresponding bunch signals without counterphasing. Counterphasing effect is evident in these figures; microwave disturbance is quieter and emittance blow-up is smaller. Similar effect is observed in the phase shake operation. The bunch flattening by lower RF voltage makes larger phase excursion in the phase oscillation of the beam particles.

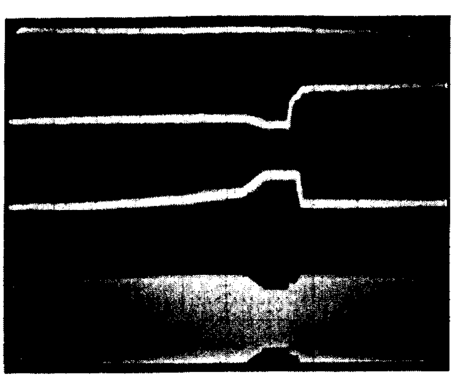


Fig. 9 Another example of counterphasing voltage. (20 ms/div)
Traces are: 1. proton number (5×10^{11}/div)
2. dr signal
3. counterphasing voltage
4. synthesized RF voltage of four cavities (40 kV/div)

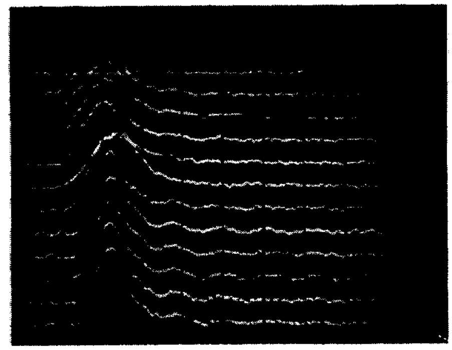
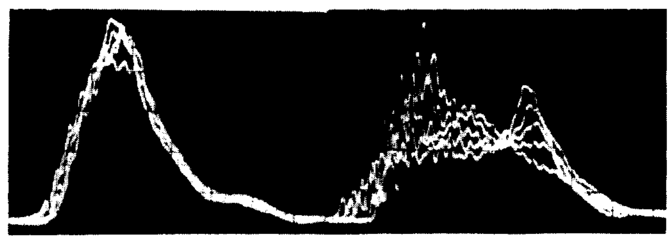


Fig. 10 Bunch flattening by counterphasing. (10 ns/div, 1891 revolutions/trace)

Therefore, the underlying principle of instability suppression will be Landau damping because larger phase excursion means larger spread of synchrotron frequencies of beam particles. These phenomena could be related to the overshoot formula.[3] If we prepare a flattened bunch with larger phase spread and smaller momentum spread before the phase transition by voltage reduction, we get a sharper bunch with smaller phase spread and larger momentum spread after the transition.



(a) counterphasing ON (b) counterphasing OFF

Fig. 11 Effect of counterphasing on the microwave instability in the bunches. Five traces are taken 2 ms after the phase jump with 341 revolutions interval. (5 ns/div)

4. Discussions

If we can increase RF voltage by implementing more RF cavities, we will probably be able to save the transition beam loss without bunch flattening; even if emittance blow-up occurs due to microwave instability, larger RF bucket will probably accept the larger beam emittance.

Systematic survey of beam equipment impedance has never been made in the 12-GeV PS. However, high frequency characteristics of wall current type beam position monitor (total 56) has been tentatively measured.[4] Resonance-like singularity has been noted at 800 MHz, very close to the frequency of microwave instability. Further study is required if the damping in the monitor chamber can suppress the 800 MHz instability at the phase transition.

We are indebted to Dr. E. Ezura for the preparation of phase shifters used in the counterphasing. We thank Dr. T. Suzuki for useful discussions.

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