IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

LONGITUDINAL BEHAVIOR OF THE BEAM IN KEK BOOSTER

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Summary

The measurements of the longitudinal beam properties and high intensity effects of the KEK booster are presented. The capture efficiency has been improved by using two kinds of cure for beam loading instabilities appeared just after injection. Operation of the second RF station in cooperation with the existing one reduces the beam loss during acceleration. Severe longitudinal beam instabilities observed at the end of acceleration have been cured by incorporating a $2f_s$ feedback loop.

Introduction

The KEK booster is a 500 MeV fast-cycling proton synchrotron with the repetition rate of 20 Hz. The design aim of using the booster is to raise the beam intensity of the 12 GeV main ring. Nine pulses of the booster are injected into the main ring to fill up its total circumference. The outline of the booster RF system was already described.[1,2] Since the beginning of operation, several improvements have been made on the RF system to increase the beam intensity and to improve the longitudinal properties of the beam.

Capture

For a single turn injection, about 90 % of the injected particles are captured. As a number of turns is increased, the efficiency is reduced to 40∿60 % depending on an operating condition and an energy spread of the linac beam. This low efficiency is mainly associated with the radial beam size enlarged up to the aperture limit in consequence of the multi-turn injection.[3,4] The RF voltage program therefore has its optimum in the sense that particles having larger momentum deviations than a cretain value are scraped with the wall. Fig.1 shows the variations of the beam intensity during capture, measured for several RF voltage programs. In the present operation the program of type No.3 is used. Further increase of the voltage makes the capture efficiency decrease because of the radial expansion of the beam.

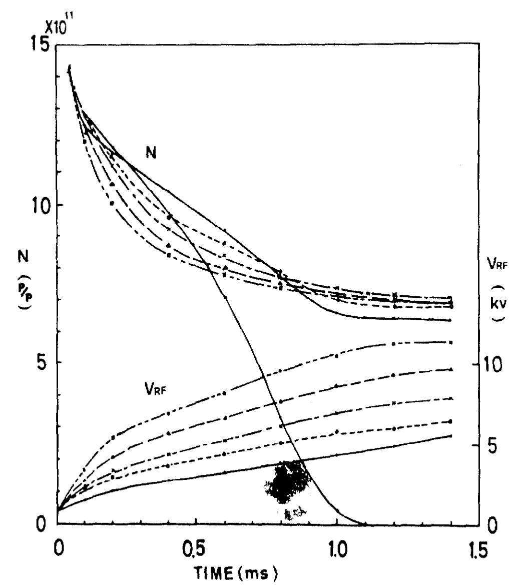

Fig.1 Number of particles just after injection (RF voltage as the parameter).

A debuncher in the injection line allows the linac energy spread to be varied over the range of 0.6 % ∿ 3.0 % at full width. Fig.2 shows the capture efficiency measured as a function of the linac energy spread; the capture efficiency is defined here as the ratio of the beam intensity at 1 ms to that at injection. The solid line in the figure shows the result for the normal operating voltage (No.3 in Fig.1) and the dashed line for the reduced voltage. A bucket filling factor defined as, (emittance of injected beam/ bucket area at 1ms), is also shown in the lower part of Fig.2. The optimum energy spread is around 1.8 %. In this case, the bucket for the normal operation would be 80 % filled at the end of capture, provided the capture were adiabatic. Larger energy spread of the injected beam exceeds the bucket area, while smaller one creates severe filamentations during bunch formation and causes particles to spill from the bucket. Besides, smaller energy spread leads to the longitudinal instabilities later in the cycle.

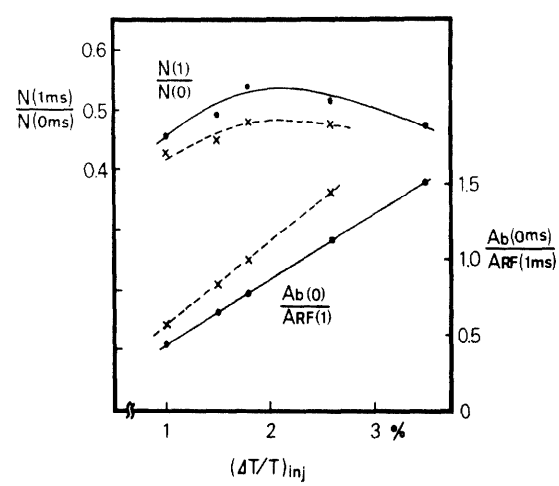

Fig.2 Capture efficiency and bucket filling factor vs. full energy spread of injected beam (solid line for normal operating voltage and dashed line for reduced one).

Compensation of Beam Loading

Most of the beam loss during 1 ms after injection is, as mentioned above, due to the large radial beam size. With the increase of the beam intensity, however, beam loading instabilities appeared in the capture region where the RF voltage is still low. The beam-induced voltage disturbs tuning of the cavity, modulates the RF voltage and causes the beam loss during the capture process. To cope with the instabilities, the shunt impedance of the cavity system is reduced by pulsing the cathode current[5] for the duration of 1 ms. By this procedure the Q value of the cavity system can be reduced from 40 to 24. This makes the RF voltage acceptably smooth unless the injected beam exceeds

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0018-9499/79/0600-3538$00.75 © 1979 IEEE

1×10^{12} ppp. Since the reduced Q value is limited to ≃20 owing to the current characteristics of the tetrode, another cure is necessary to overcome heavier beam loading.

Recently a fast compensation of the beam loading was successfully tested. A block diagram of the test circuit is shown in Fig.3. A fundamental component of the bunch signal is fed back into the first stage of the RF amplifier system, in order to cancel the beam-induced voltage on the cavity. Fig.4 shows the RF voltages in the early stage of acceleration for the injected beam intensity of 1.5×10^{12} ppp; Fig.4(a) was taken without any cure and Fig.4(b) with both the reduced Q and the fast compensation. It is expected that a proper operation of the fast compensation in addition to the reduction of the Q value cures the beam loading instabitlies even when the injected intensity is increased further.

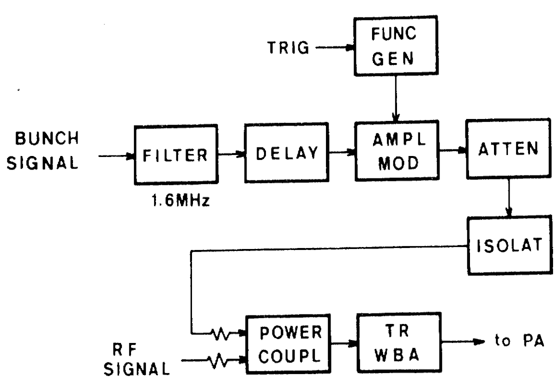
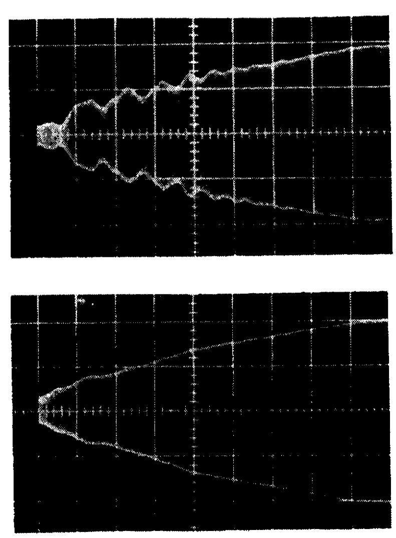


Fig.3 Test circuit for fast compensation of beam loading.

(a)

(b)



(V: 1.8 kV/div , H: 0.2 ms/div)

Fig.4 RF voltage in the early stage of acceleration; (a) without any cure, (b) with reduced Q and fast compensation.

Transmission after Capture

A transverse instability of the head-tail type has been observed around 17 ms after injection. This instability is considered to be due to the interaction of the beam with the kicker magnet.[6] It can be avoided to some extent by operating the machine with the properly adjusted parameters, such as the timing of the injection bump magnets, the RF frequency at the injection and the energy spread of the linac beam. A basic cure for the instability is achieved by exciting sextupole and octupole correction magnets.[6]

Under the condition free from the head-tail instability, a beam transmission from 1 ms after injection to the end has been limited to 75 ∿ 80 %. The voltage measurement showed that the bucket area was not enough. By the improvement of the cavity system, the maximum voltage was increased from 15.5 kV to 17.5 kV. The beam transmission was then improved to 80 ∿ 86 % at the intensity of 6×10^{11} ppp. A typical bucket area obtained after the improvement is shown in Fig.5 together with the measured voltage and

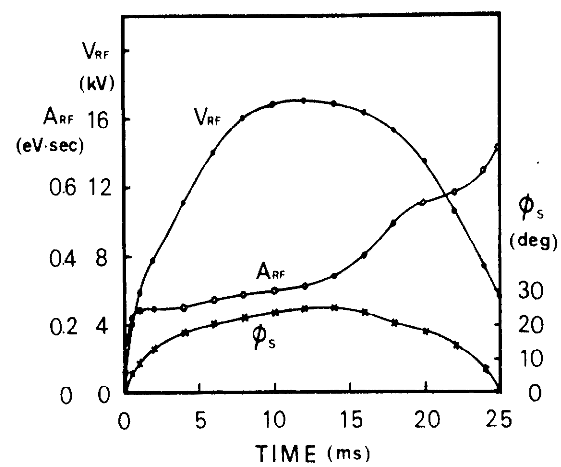
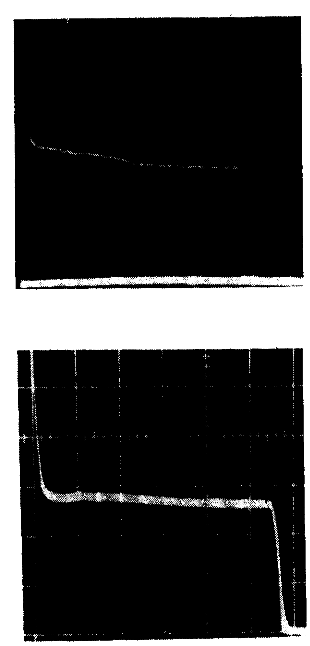


Fig.5 RF voltage, bucket area and equilibrium phase angle in present operation.



(a) with single RF station

V: 2×10^{11} ppp/div

H: 5 ms/div

(b) with two RF stations

(five pulses superposed)

Fig.6 Number of particles during acceleration.

equilibrium phase angle. Fig.5 suggests that the bucket area should be increased further during the first half of the cycle because a considerable emittance blow-up is expected. The second RF station has been installed to increase the maximum voltage. Simultaneous operation of the two RF stations improves the beam transmission to about 90 % as shown in Fig.6. It saves the beam loss which appeared in the early part of acceleration, but not the gradual decrease of the intensity in the following part. A mechanism of the gradual decrease is now under investigation. The simultaneous operation, however, deteriorates bunch stability, so some modification is necessary for daily operation.

Bunch Stabilization

During the running of the KEK main synchrotron, longitudinal stability at the end of acceleration of the booster has been increasing problem to get high intensity beams as stable as possible for main-ring-injection. At lower intensities than 3×10^{11} ppp, the problem could be handled by operating the machine with a properly chosen energy spread from the linac. It is, however, very difficult to damp the instability at higher intensities than 3×10^{11} ppp with this procedure. A damping system has been developed and tested on the machine. Complete stability is obtained at the highest intensities of 6.4×10^{11} ppp.

Longitudinal instability is observed by sidebands appearing around the revolution frequency. The KEK booster, like many other proton synchrotrons, incorporates a beam feedback system. It eliminates largely coherent phase oscillations of the bunch which is a sideband of the synchrotron frequency f_s or a dipole mode of instability. But the beam feedback has no effect on the bunch shape oscillations in first approximation. A main mode of the instability in the booster is a quadrupole type or the oscillation at $2f_s$. A fact that a leading edge of a bunch is sensitive to bunch shape oscillation is utilized to detect the feedback signal.

A block diagram of the feedback loop is shown in Fig.7. A phase pickup signal is passed through a saturable amplifier and a fast discriminator to maintain constant damping rates independent of intensity. The detector is a digital phase detector which determines the "lead" or "lag" phase relationship and the time difference between the leading edges of the waveforms. The detector is followed by a tracking bandpass filter tuned to $2f_s$. The output signal of the filter is fed into a linear gate and a phase shifter to give a proper phase relation to the cavity. Finally the signal is added to the amplitude modulation signal. Fig.8 shows the effect of this additional modulation for the acceleration voltage. The cure is now used during the last 1/3 of the cycle. The intensities well over 6.4×10^{12} ppp can be accelerated with this technique.

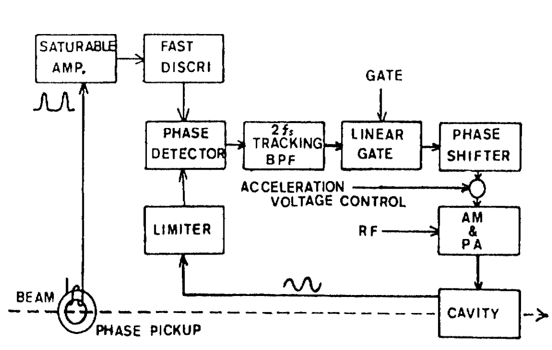
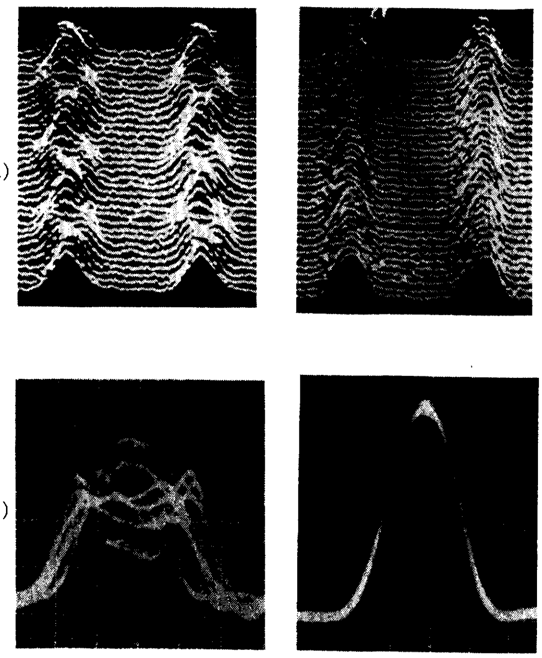


Fig.7 Block diagram of the $2f_s$ feedback loop.

(a)

(b)



without feedback with feedback

Fig.8 Effect of the $2f_s$ feedback loop
(a) mountain-range display (16.7 μsec/trace),
(b) superposed (20 nsec/div).

Acknowledgement

The authors wish to thank Dr. J.E. Griffin of Fermilab for his practical advice on the improvement of the RF system.

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