OPERATION OF THE RF SYSTEM AT THE KEK PS

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ABSTRACT: The development of the KEK-PS rf system for this 10 years and the recent operation are summarized.1) The measured emittance variations during acceleration are also presented.

DEVELOPMENT OF THE KEK-PS RF SYSTEM

The operation of the KEK-PS for physics experiments started in 1977. In 1980, the Booster Synchrotron Utilization Facility(BSF) started operation. The beam intensity of the Booster and that of the Main Ring were $\sim 6\cdot 10^{11}$ppp and $\sim 4\cdot 10^{12}$ppp, respectively. The ion source was changed from proton to H^- ion with employing the charge-excahnge technique at the Booster injection in 1983. In 1985, the 40MeV linac was installed. This improvement has increased the intensity of BSF beam to $\sim 2\cdot 10^{12}$ppp at the Booster injection. For an increased beam intensity at the Booster, the stability of the rf system becomes substantial for steady operation of the KEK-PS.

We have analyzed the feedback loops in the rf system on the basis of control theory. Fig.1 shows a signal flow diagram of the KEK-PS rf system. The diagram shows all of the connections of the feedback loops in the system. The analyzed systems are the cavity tuning loop, the Automatic Voltage Control loop (AVC), and the beam feedback system1). The stability of the cavity tuning system is essential for a steady operation of the rf system. In order to increase the loop gain of the automatic cavity-tuning system, an improvement of the bias power supply was necessary. The adjustment of the control circuit in the bias power supply increased the bandwidth of the cavity-tuning loop to ~1kHz. For the Main Ring cavity-tuning system, the bandwidth is ~3kHz.

Parallel operation of the two accelerating stations in the Booster has started from 1979.

In 1983, we installed the cavity phase-lock loop both for the Booster and the Main Ring. The system can be used for a counter-phasing technique with which the effective accelerating voltage per ring can be reduced without a reduction of the rf voltage at rf cavities.

In the above analyses of the feedback loops, we had neglected the beam loading effect. We started the analysis of the stability of the rf system in the presence of the beam loading since 1986. The analysis is based on the transfer function method.[2] The analysis shows that the beam loading shifts the cavity resonating frequency to several-10kHz higher than the accelerating frequency(before transition). This phenomenon is clearly observed at the transition in the Main Ring ferrite bias current; the bias current(the resonating frequency of the cavity) suddenly decreases at the transition(Fig.2b). This analysis also shows that the transfer function of the cavity for a modulation signal reduces its value with increasing loading beam current.[3] This means that feedback loops in the rf system reduce their open loop gains with increasing the circulating beam current. Therefore, even under an operating condition of below the loading stability limit, the gain of the feedback loop must be made to be as large as possible.

The KEK-PS has also been accelerating deuteron beam since 1991. The accelerating frequency range of the Booster is reduced from 2.25MHz ~ 6MHz to 1.16MHz ~ 4MHz by connecting vacuum capacitors across the accelerating gap. For the Main Ring, the frequency range is extended from 6 ~ 8MHz to 4 ~ 8MHz by installing a new bias power supply having a output current of 1500A. The lowest frequency is also reduced by connecting vacuum capacitors across the gap.[4]

In 1992, the following electronic modules were moved from the Booster accelerator room to an auxiliary control room for the Booster apparatus. The moved modules are the low level electronic circuits of the cavity-tuning system, that of the AVC and the cavity phase-lock system. These circuits had suffered from a noise from the high power rf system. This improvement has eliminated the noise from the circuits.

RECENT OPERATION OF THE KEK-PS RF SYSTEM

The scheduled operation of the KEK-PS repeats with a period of three weeks. The intensity of the Booster beam is $\sim 1.2 \cdot 10^{12}$ppp at the start of the operation and increase to $\sim 1.6 \cdot 10^{12}$ppp within a few days. The KEK Booster steadily accelerates the beam with an intensity of $1.6 \cdot 10^{12}$ppp, which corresponds to a 1.54A average beam current at 500MeV-top energy. Since the accelerating system has 2 gaps, the amplitude of the loading current(I_L) onto the power amplifier amounts to 4.6 ~ 6.2A depending upon the bunch width. The shunt impedance at the drive terminal is 600Ω, therefore the drive current of the rf cavity(I_D) is 5A at a 6kV accelerating voltage. The relative loading Y, defined by $Y = I_L/I_D$, is 0.94.

The beam loading effect reduces the cavity transfer function for a modulation signal. The analyses in Refs. 2) and 3) say that the rf system becomes unstable for a loading of $Y \sim 2$. The rf system of the Booster at the top energy is still free from the loading instability.

At beam injection average circulating current is 0.51A and the loading current(I_L) is ~1.54A. The shunt impedance of the cavity at the drive terminal is ~1kΩ; therefore, we must increase the accelerating voltage to a value greater than 3kV by the time a bunch is established(~100μs after the beam injection). In order to reduce the relative loading at the beam capture process, we keep the rf voltage at an accelerating station to 5kV and reduce the effective accelerating voltage by the counter-phasing technique(Fig. 3(a)). This technique is effective for an operating region where the relative loading has a value of less than 1.$^{3)}$

Adoption of the counter phasing technique solves three difficulties in the Booster rf system, one is the loading problem at beam injection(explained above); the other two difficulties come from a limitation of the bandwidth of the bias power supply. At beam injection, the bias power supply experiences two perturbations: the first one comes from a shift in the cavity resonating frequency due to the beam current; the second one comes from the dependence of the ferrite permeability on the flux density. An abrupt increase of the accelerating voltage increases the bias current. At the beam injection, the output current of the bias power supply is minimum, and its bandwidth is also narrow. Therefore, the beam injection period is the most unstable operating time for the cavity-tuning system. The unstable oscillation of the bias current due to the perturbations at the beam injection was observed at the output of the phase detector in the cavity-tuning system. The oscillation had reduced the capture efficiency of the injected beam. This unstable oscillation has been removed by increasing rf voltage to 5kV before the beam injection and by employing a second-order compensation technique$^{1)}$ for the cavity-tuning loop.

The problem concerning the longitudinal beam emittance is a serious problem for the Main Ring injection and for the extraction system of the Booster at high intensity.

The emittance of the beam from the linac is typically 0.35eV·s which is calculated from Δp/p of linac beam. As shown in Fig.4, the emittance blows up to ~ 0.6eV·s for the BSF beam at an intensity of $1.6 \cdot 10^{12}$ppp. The blow-up occurs during both an adiabatic capture process and acceleration. These emittance values are calculated from the measured bunch width(in the unit of rf phase) and the accelerating voltage. In the calculation, an ellipse approximation of the bunch in the phase space is employed. In the case of the Booster, the space charge force in the bunch is not substantial. Since the width of the bunch is not so short, it gives an error of nearly 10%. The results at 15ms and 20ms in Fig.4 contain errors in the approximation. The dependence of the longitudinal emittance at 1ms on the date of the measurement comes both from variation of the linac emittance and from the adjustment of the growing bucket. For a low intensity, the emittance growth during the acceleration is small. The quadrupole mode damping system[1] is used from the start of the capture process. Fig.3(b) is an example of the fast intensity monitor during the capture process. When the ramp speed of the accelerating voltage is faster than the example, a strong quadrupole oscillation is observed.

The longitudinal acceptance of the Main Ring is determined by the effective rise time of five kicker magnets at the Main Ring, and the value is ~0.4eV·s. The emittance of the Booster increase to 0.4eV·s at $4.5\cdot10^{11}$ppp for the Main Ring beam. The injection phase error and the mismatch between the rf buckets of the Booster and the Main Ring increase further the phase space area of the injected beam. As a result, the width of the bunch circulating in the Main Ring increases, and a certain part of the protons in the bunch are kicked by the rising head of magnetic field of the kicker magnets at the next beam injection. This effect causes a beam loss at the beginning of the acceleration, where the dynamic aperture of the Main Ring is minimum.

The emittance at an intensity of $1.6\cdot10^{12}$ppp for the BSF is ~0.6eV·s. On one hand, the rise time of the magnets is designed to be ~80ns. On the other hand, the large emittance value results in a smaller bunch-to-bunch space of the circulat-ing beam in the Booster and limits the permitted rise time of the extraction kicker magnets. In order to maintain an 80ns bunch-to-bunch spacing, we must increase the accelerating voltage at the extraction for the BSF to 12kV. As a result, the momentum spread of the extracted beam for the BSF is far larger than that of the Main Ring beam.

At the phase transition of the Main Ring, both the micro-wave instability and the longitudinal quadrupole mode oscillation are observed. This quadrupole mode oscillation is caused by the mismatch between the rf bucket and the bunch due to the space charge force. The longitudinal emittance blows up to nearly 5-times as large as the value before the transition. The project to shift the transition energy to above 12GeV-top energy has been stopped, because of the requirement of physicists on the internal target channel, where one of four quadrupole doublets has to be installed. The four quadrupole doublets vary the dispersion function in the Main Ring and shift the transition energy.

The following list is an operational result for this 10 years.

Operation time from April 1982 to March 1993; 37270h
The time stopped due to machine troubles; 1426h(3.8% of the operation time)

The time of trouble due to

		Linac;	354h(24.8% of the trouble-time)
40MeV BT;	265h(18.6%)	500MeV BT;	187h(13.1%)
@ Booster RF;	110h(7.8%)	Pre-inj.;	119h(8.3%)
Main Mag. PS;	98h(6.9%)	@ Main Ring RF;	63h(4.4%)

The time of the machine troubles due to the Booster and the Main Ring rf systems is more than 12% of the total machine trouble time. It could be reduced to less than 10%, if a more systematic diagnostic procedure was established.

CONCLUSIONS

The elementary analyses1) based on control theory help the diagnosis and the tuning of the rf system. The reliability of the rf system at the KEK-PS is achieved by the effort of all members of the KEK-PS RF Group.

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REFERENCES

1) S.Ninomiya et al, "DEVELOPMENT OF THE RF SYSTEM AT KEK-PS." KEK Report, 1993.
2) F.Pedersen, IEEE NS-22, p.1906, 1975.
3) S.Ninomiya, "Beam Loading Effect on RF ....(in Japanese)" KEK Report, 89-18.
4) S.NINOMIYA et al, "Improvement of the RF System .... for Deuteron Accel."
Proc. of 8th Symp. on Accel. Sci. and Tech., p.167, 1991.

FIGURE CAPTIONS

Fig.1 Signal flow diagram of the KEK-PS RF system.

Fig.2 (a) Booster bias current changes from 300A to 2300A sinusoidally with a repetition of 50ms. Variation of the cavity tuning phase error is also shown in a scale of 40°/div. (Horizontal; 5ms/div.)

(b) The upper trace is the variation of the accelerating frequency from 6MHz to 8MHz at the KEK-PS Main Ring rf system. The middle is the bias current. It shows the jump in the resonating frequency at the transition. The lower trace is the cavity tuning error in 20°/div. (Horizontal; 0.2s/div.)

Fig.3 (a) Counter-phasing technique at the Booster beam injection reduces the rf voltage at the Booster accelerating gap(lower trace, 5kV/div.) and makes the effective accelerating voltage per revolution(upper trace, 6kV/div.) Horizontal; 0.5ms/div.

(b) Growth of the bunch(lower trace) at the Booster injection is compared to the accelerating voltage(upper trace).

Fig.4 Variation of the longitudinal emittance of the Booster beam during the acceleration.

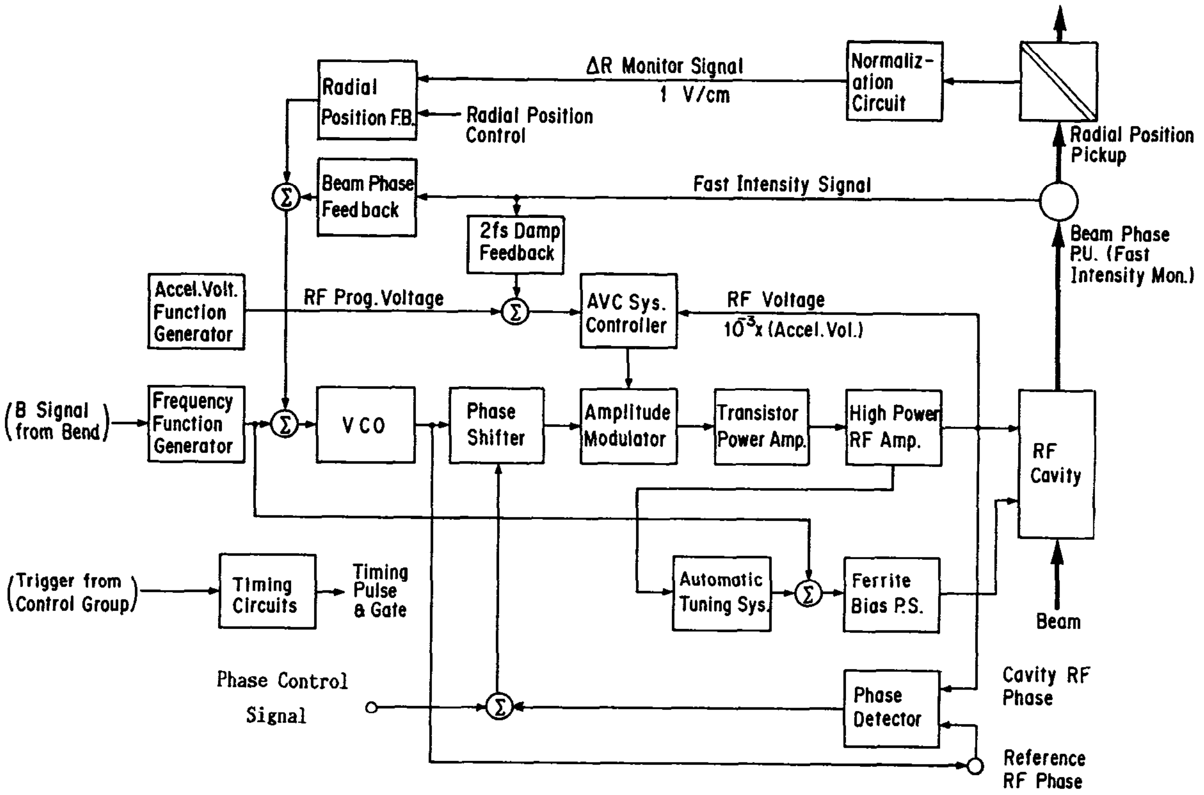

Fig. 1

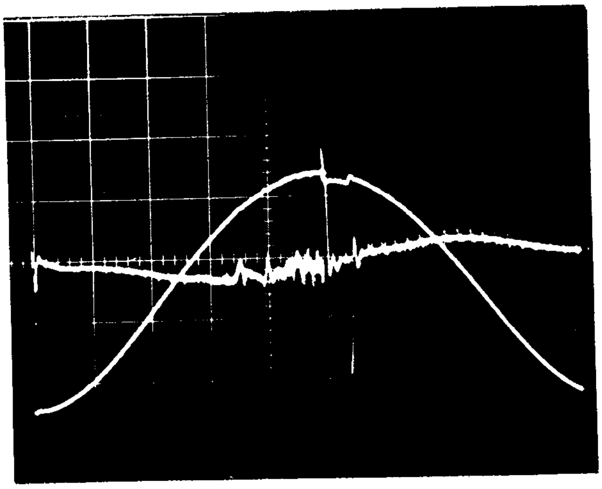

Fig.2(a)

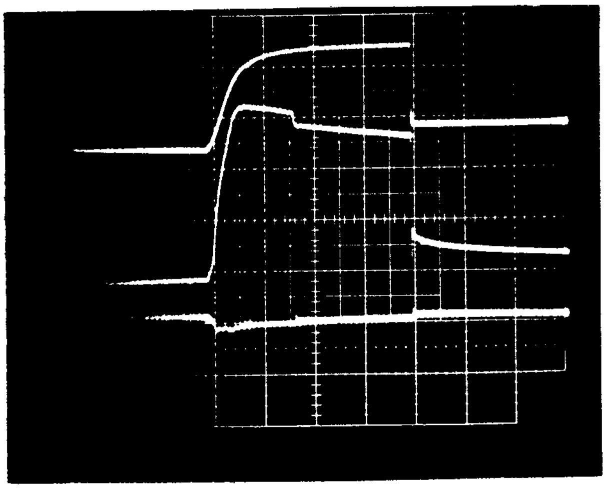

Fig.2(b)

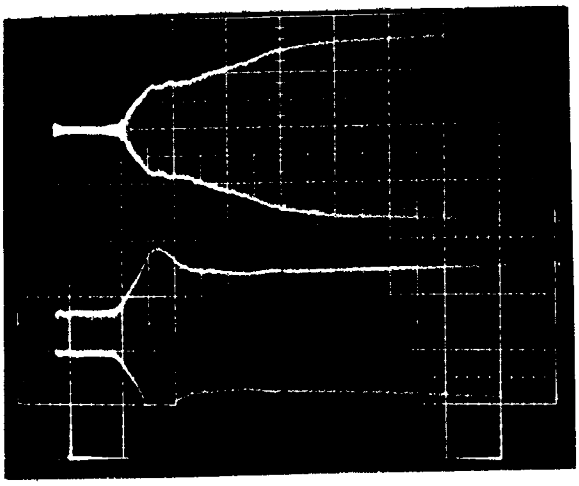

Fig.3(a)

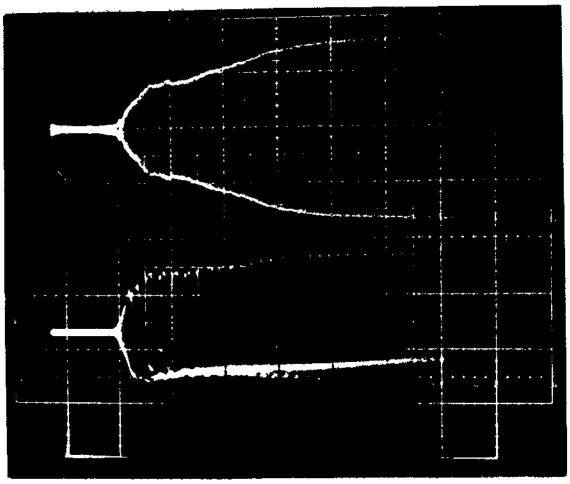

Fig.3(b)

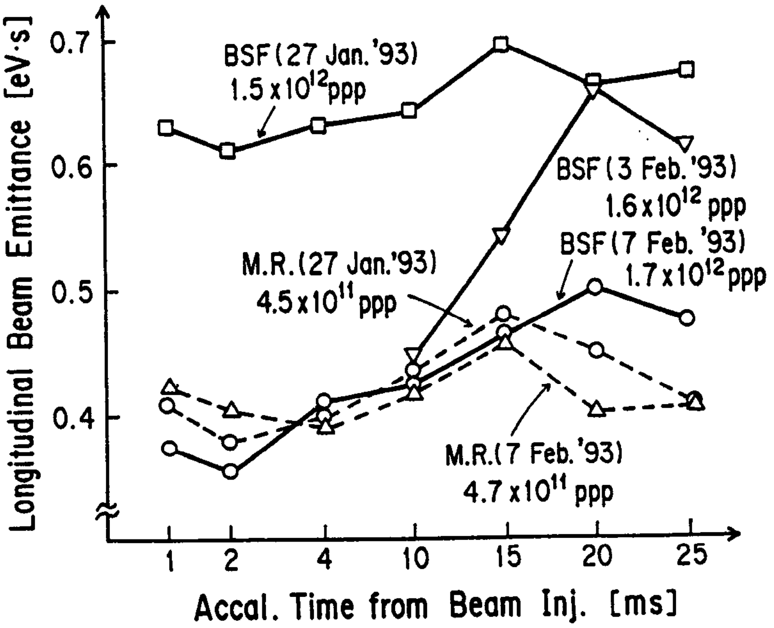

Fig. 4