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RF ACCELERATION IN KEK MAIN RING

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Summary

A description of the RF system and measurements of some longitudinal phenomena of the KEK Main Ring are presented. The beam loss at the phase transition has been reduced by the improvement of the radial position detector and by the stabilization of quadrupole oscillations. The debunching for slow beam extraction is done by two successive frequency jumps with simultaneous reduction of the RF voltage.

Introduction

The KEK Main Ring is a slow-cycling 12 GeV proton synchrotron with a 500 MeV fast-cycling booster. Nine booster pulses injected at the front porch are accelerated to the final energy by three accelerating stations. A frequency-controlled signal from a low level RF system is distributed to the three stations.

The first 8 GeV beam was achieved on March 4, 1976. At the early operation, the beam transmission from injection to extraction was very low. It became clear that beam control via the RF system was the crucial problem. With improvements of the beam control system, the beam intensity has been increased month by month and reached the first target of 2×10^{12} ppp at 12 GeV on July 24, 1978. In this paper, the outline of the RF system and the present status of its operation are presented.

RF System Parameters

The machine parameters of primary importance to the RF system and the overall RF system parameters are summarized in Table I.

Table I RF System Parameters

Injection energy	500 MeV
Extraction energy	12 GeV
$\Delta p/p$ at injection	$\pm 3 \times 10^{-3}$
Harmonic number	9
RF frequency range	6 - 8 MHz
Accelerating voltage	60 kV
Number of cavities (two gaps/cavity)	3
Shunt impedance of the cavity	10 kΩ
Ferrite bias current	80 - 370 A
Synchrotron frequency	≤ 4 kHz
Energy gain per turn	20 kV
Equilibrium phase angle	20 deg
Total peak ferrite loss	18 kW
Total peak power delivered to beam	8 kW

High Power System

A system of each station is similar to that of the booster,[1,2] and is shown in Fig.1. Main components of each station are an RF power amplifier, an accelerating cavity and a ferrite bias supply.

The power amplifier is capable of providing 30 kW to the cavity. The final stage consists of a couple of vapour-cooled tetrodes, working in grounded-cathode push-pull arrangement and in class AB. The driver stage is a 400-watt wide-band amplifier using four tetrodes in parallel push-pull arrangement. The 0.2-watt signal from the low level system is modulated in amplitude with the PIN diodes. This signal is amplified up to 4 W by a transistorized pre-amplifier and then delivered to the driver. The final and driver stages are placed close to the cavity in the Main Ring tunnel, while the other circuits are located in the local control room. Control of the cavity gap voltage to agree with an input reference is provided by a negative feedback loop.

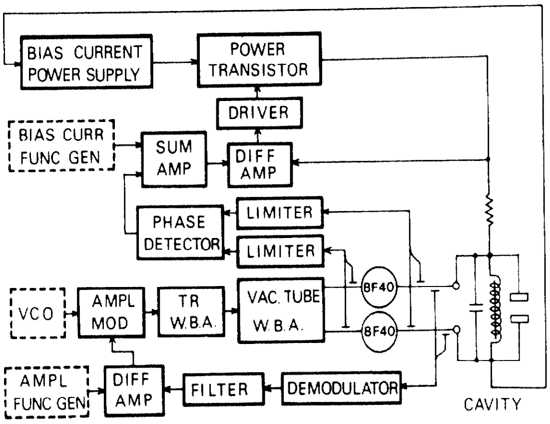

Fig.1 Block diagram of the high power system.

The accelerating structure is a coaxial system consisting of two foreshortened push-pull quarter wave cavities connected in parallel. It is loaded with 40 ferrite rings, 450 mm OD, 230 mm ID and 25 mm thick. The ferrite is of iron-deficient nickel-zinc type with a small amount of cobalt ion substitution. The measured properties of the ferrite are shown in Fig.2. The shunt impedance of the cavity is 10 kΩ and the average power loss of the cavity is 5 kW.

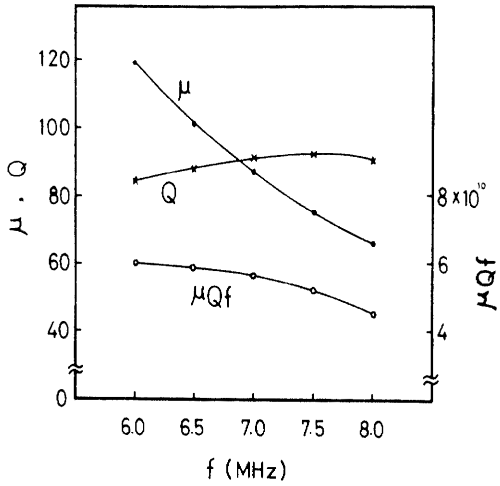

Fig.2 Average properties of ferrite rings.
μ: permeability, Q: quality factor

The ferrite bias supply can provide 500 A to the cavity. Its final stage uses 5 water-cooled high power transistors connected in parallel as a grounded-emitter configuration. The automatic tuning is achieved in

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such a way that the phase difference between grid and anode voltages of the RF power amplifier is detected and used to control the bias current. To improve the accuracy and the stability of the tuning system, a program signal is added to the output of the phase detector. Sweep range of the bias current is from 80 A for 6 MHz to 370 A for 8 MHz.

Low Level System

Fig.3 shows the block diagram of the low level system. VCO is an LC oscillator, C of which is controlled by the external voltage. Because the linear region of the change of capacitance vs. control voltage is narrow, the VCO operates at higher frequency (46 MHz - 48 MHz) than the accelerating frequency (6 MHz - 8 MHz). The mixing-down of the frequency by a local oscillator (40 MHz) generates the accelerating frequency. Between the local oscillator and the mixer, a voltage controllable phase shifter is inserted. It operates at the constant frequency (40 MHz). The control signal of the phase shifter is the summing signal of beam radial position, dB/dt, and correction signal.

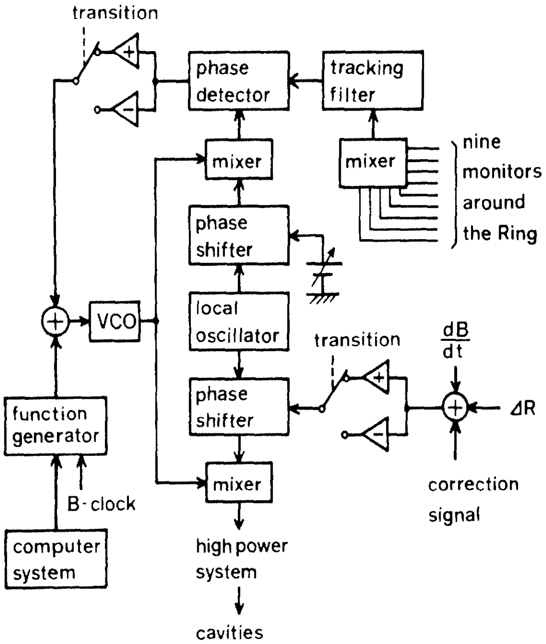

Fig.3 Block diagram of the low level system.

VCO is controlled with the a program signal and a phase-locked loop (PLL) with the beam phase. The program signal is generated by counting B-clock,[3] which corresponds to 0.1 G increment of guiding field, and converting the corresponding digital data to analog output. The beam signal for PLL is a mixed signal of nine wall current monitors located in equal spacing around the Main Ring. The mixed signal is fed to a tracking filter to pick up only the component of accelerating frequency. Then it is clipped and fed to a mixer to compare the phase with a mixed-down output of VCO.

The reason of using the sum signal of nine monitors is that even if some of the bunches coming from Booster drop out, the signal with nonuple of the revolution frequency of the beam (RF signal) can be fed to PLL, and even if each bunch contains the different number of particles, its effect does not come out in the RF signal. Fig.4 shows the difference between the output of a single monitor and the mixed output of nine monitors.

A minicomputer system with a set of external memories is adopted to control the program signals, timing signals, and dc bias voltages.

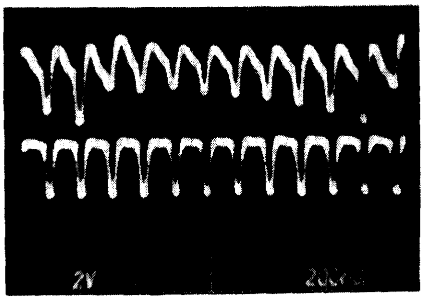

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Fig.4 Beam signal of a wall current monitor (top). Mixed signal of nine wall current monitors (bottom).

Phase Transition

The beam loss at transition became a serious problem with increase of the beam intensity. The noticeable losses were first observed when the intensity exceeded $\simeq 6 \times 10^{11}$ ppp, and the amount of loss reached over 20 % at the intensity of $\simeq 1.5 \times 10^{12}$ ppp.

The severe bunch shape oscillations mainly of quadrupole type were observed whenever the beam lost its considerable part at transition. Oscillations at twice the synchrotron frequency appeared also on the radial position signal, though the position detector should be insensitive to the higher modes of synchrotron oscillations. From this fact it was deduced that the position detector intensified bunch shape oscillations via position feedback loop. The position detector system was then thoroughly re-examined and improved. The replacement of the pick-up electrode by the larger one[4] provided the clean bunch signal with greatly improved signal-to-noise ratio. This made it possible to remove the signal processing circuits, such as the amplifier, the noise filter and the rise time integrator. This improvement completely eliminated the bunch structure from the poistion signal and improved the beam transmission through transition. Further reduction of the loss was achieved by incorporating a feedback loop for damping the quadrupole oscillations. The envelope of the bunch signal is, in proper phase relation, fed into the phase shifter. At present, the amount of the beam loss at transition is around 5 % on the average even when the beam intensity exceeds 1.7×10^{12} ppp. Fig.5 shows the beam intensities before and after the improvements.

Fig.6 shows the longitudinal emittance blow-up obtained from the measured bunch length, by using the definition, (measured bunch length)^2/(calculated bunch-length without blow-up)^2. The emittance gradually grows before transition and blows up drastically just after transition. Fig.7 is the mountain-range view of a bunch during 18 ms after transition. The bunch length takes its minimum at a few msec after transition due to the change of space-charge force from defocusing to focusing at transition. It is observed from Fig.7 that the very fast blow-up occurs right after transition and is followed by the slow blow-up. The fast blow-up is presumably due to the negative-mass instability and the slow one is due to the bunch-length oscillations caused by the space-charge effects.

The amount of the longitudinal emittance blow-up at transtion was estimated for several blow-up mechanisms. The longitudinal space-charge effects and the negative-mass instability could cause considerable

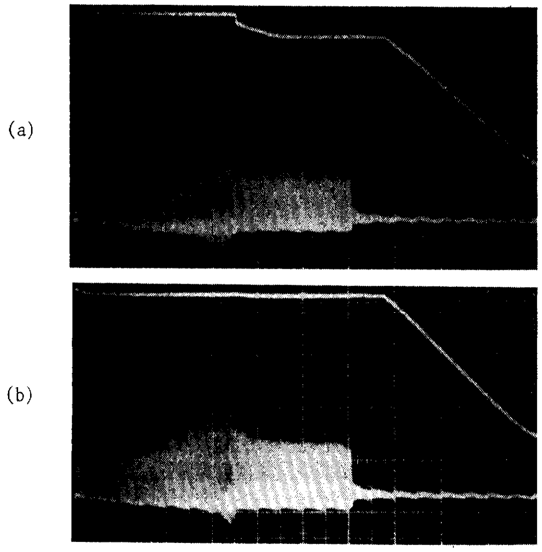

Fig.5 Number of particles (top) and bunch signal (bottom) during acceleration and extraction (a) without and (b) with the transition cures. Intensity is 1.6×10^{12} ppp (100 msec/div).

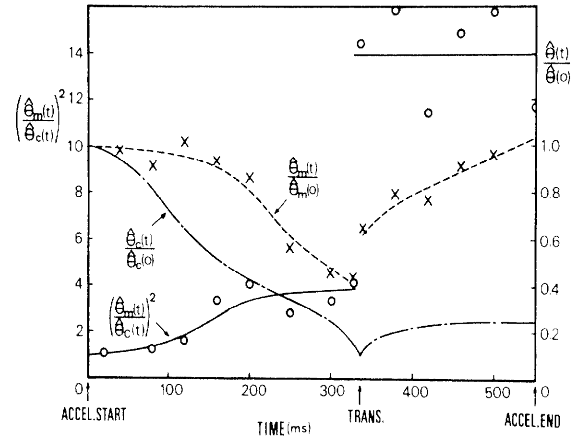

Fig.6 Measured bunch-length and longitudinal blow-up; $\hat\theta$ represents full-width at half of a bunch and suffixes "m" and "c" denote measured and calculated respectively.

Fig.7 Mountain-range view during 18 msec after transition (340 μsec/trace and 5 nsec/div).

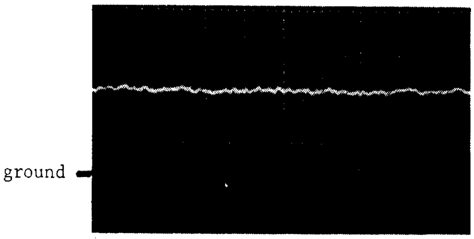

Fig.8 RF structure in slow beam spill (1 μsec/div).

blow-up at the present intensity of $1 \sim 2 \times 10^{12}$ ppp, while the effects of the transverse space-charge and the beam-cavity interaction are negligible. Further investigation is necessary on the effects of non-linear magnetic fields.

Debunching

The beam at the top energy is required to be well debunched for the slow extraction which utilizes the half-integer resonance.5) Non-adiabatic debunching is used because a certain momentum spread is necessary to ensure the stability against rebunching induced by beam-equipment interactions. The debunching method now used is not so sophisticated but contributes to get a tolerably good beam spill.

The method includes two successive frequency jumps; the first jump is for debunching the beam and the second one for preventing the debunched beam from rebunching. The RF frequency synchronizing with the beam is jumped to a nonsynchronous frequency by opening the PLL. The nonsynchronous frequency to give a well debunched beam is found to be 2 kHz - 3 kHz away from the synchronous one. An optimum RF voltage at the frequency jump is also measured. Although no sharp peak is distinguishable, a considerable voltage (more than a third of the normal operating voltage) is desirable to scramble the beam. During scrambling, the energy spread of the beam is increased as the beam drifts with respect to the nonsynchronous RF buckets. A large energy spread makes a stream of particles more homogeneous, thus reducing its RF structure. Soon after the first frequency jump, the RF voltage is reduced to a very low value not to affect the beam. A rebunching occurs when some equipment of the machine has a resonant frequency close to a harmonic of the revolution frequency of particles. To avoid the re-bunching induced by the interaction with the RF cavities, the frequency is jumped again, at some 30 msec after the first jump, to a frequency well apart from multiples of the revolution frequency. By this procedure, the RF structure in the beam spill is reduced to several precent modulation (Fig.8).

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