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RF ACCELERATION IN KEK BOOSTER

M. Kondoh, S. Takeda, E. Ezura, Y. Mizumachi, H. Nakanishi, T. Ieiri,
K. Kudoh, K. Ebihara, and M. Toda

National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, 300-32, Japan

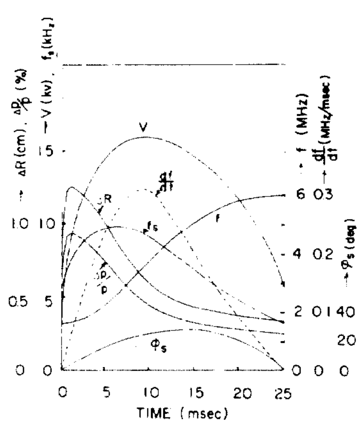
Introduction

The KEK booster synchrotron is a rapid-cycling machine with a repetition rate of 20 Hz. The RF system has been designed for accelerating the proton beam injected at 20 MeV up to its final energy of 500 MeV. The booster succeeded in accelerating 8×10^{10} protons/pulse to the designed energy on Dec. 12, 1974. Since then the beam intensity has been steadily increased to 5.7×10^{11} protons/pulse with adjustments and improvements of the machine components, especially of the RF system. In this paper, the outline of the RF system and the present status of its operation are presented.

Main parameters characterizing the RF system are listed in Table 1. Accelerating parameters and the estimated beam characteristics are shown in Fig.1.

Table 1 Acceleration Parameters

Energy gain per turn (maximum)	7.07 keV
Maximum RF voltage	16 kV
Programmable range of V_{RF}	0.2-18 kV
Accelerating frequency	
at injection	1.62 MHz
at ejection	6.03 MHz
RF harmonic number	1



V = amplitude of accelerating voltage

ΔR = radial spread of the beam by synchrotron oscillation

Δp = momentum spread of the beam

f = accelerating radio frequency

f_s = frequency of synchrotron oscillation

ϕ_s = equlibrium phase angle

Fig.1 Parameters of acceleration and estimated beam characteristics.

High power system

The high power system consists of an RF power amplifier, an accelerating cavity and automatic cavity tuning devices. The parameters of the accelerating station are summarized in Table 2. Fig.2 is a schematic diagram showing the major components of the high power RF system.

Table 2 Parameters of the Accelerating Station

Parameters and performances of the RF power amplifier

Maximum output power	80 kW
Operation class (of the power stage)	AB
AVC unity gain frequency	30 kHz
AVC low frequency gain	20 dB
Gain variation over the frequency band	0.5 dB
Amplitude linearity (0.2 kV to 5 kV)	0.5 dB

Parameters of the accelerating structure

Total length	1654 mm
Cooling water flow	70 ℓ/min
Cavity RF current (maximum)	340 A
Cavity impedance	1 to 4 kΩ
Cavity quality factor	20 to 60
Average ferrite loss	15 kW
Mean power density in ferrite	0.12 W/cm^3
Maximum beam loading	8 kW

Performances of tuning system

Unity gain frequency	2.5 kHz
Low frequency gain	45 dB
Open loop phase margin	60°
Tunig accuracy	3°

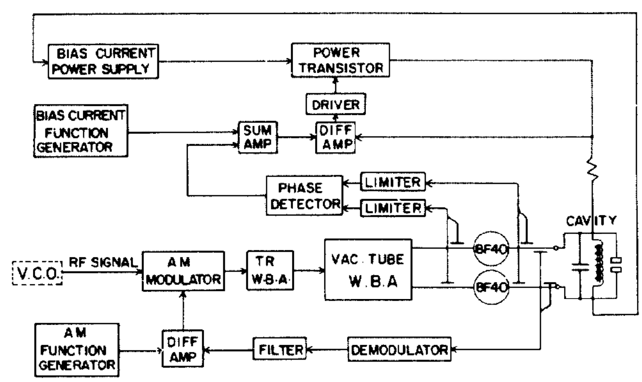


Fig.2 Block diagram of the high power system.

RF Power Amplifier

The RF power is fed to the cavity by the 80 kW RF power amplifier located in close to the cavity through the 40 cm long shielded Lecher wires. The final stage consists of four vapour-cooled tetrodes (8F40) working in grounded-cathode parallel push-pull arrangement. Class AB operation is used in consideration of the balance of the linear gain characteristics and the plate efficiency.

The driver stage is the 800 Watt vacuum tube wide-band push-pull amplifier operating in calss AB. The pre-amplifier stage using transistors amplifies the 0.2 Watt input signal up to 8 Watts and delivers it to the driver.

To obtain the programmed accelerating voltage shown in Fig.1, the amplitude of the input RF signal is modulated by the PIN diode in accordance with the envelope waveform from the function generator. The automatic voltage control system is used to stabilize the output voltage against the variation of the cavity impedance with the frequency and beam loading.

RF voltage program was determined by the following way. A program of the most economical RF voltage, to make the beam size in the phase space just fit to the RF bucket[1] was analytically obtained assuming adiabaticity of parameters on acceleration. However, this program brought a low capture efficiency, then the various voltage patterns at the injection period (during 1 ms after the injection) were tried by computer calculations to get the efficient capture. The calculations showed that the pattern of $1-e^{-\alpha t}$ with a low offset voltage, could bring on the fairly high capture efficiency. The voltage at the extraction is determined by the rise time of the extraction kicker. The program from 1 ms to about 20 ms is similar to the designed one, and joins smoothly to the extraction voltage.

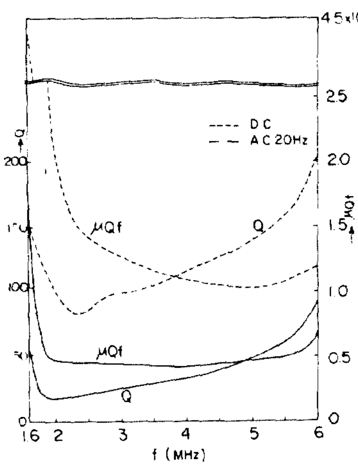
Accelerating Cavity

The accelerating structure is a coaxial system consisting of two foreshortened push-pull quarter wave cavities connected in parallel. To be tuned over the frequency band, it is loaded with 32 ferrite rings, 500 mm O.D., 224 mm I.D. and 25 mm thick, arranged in four stacks of eight.

Each stack is made to have the same permeability and the same loss at high RF flux density. Each ferrite ring is sandwitched by cooling copper discs made of rectangular hollow conductors.

Ferrite property is one of the most important factors in designing a high power RF system for a rapid cycling machine, because magnetic loss of the ferrite increases drastically with the sweep speed of a biasing field. Fig.3 shows the properties of the ferrite chosen, among many candidates, as the material to be loaded in the booster cavity.

Time variation of the powers dissipated in the cavity and delivered to beam are shown in Fig.4, together with the RF flux density in the ferrite.



μ = RF permeability of the ferrite

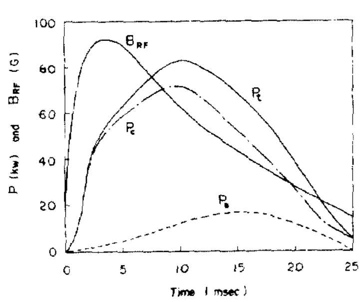
Q = quality factor of the ferrite

f = frequency

---; data for DC biasing field

——; data for AC biasing field

Fig.3 Properties of the ferrite.



P_c = loss power, dissipated in the cavity

P_b = power delivered to the beam

$P_t = P_c + P_b$

B_{RF} = RF flux density

Fig.4 Time variation of the loss power.

Cavity Tuning

The cavity is tuned to the accelerating frequency by impressing the biasing magnetic field on the ferrites. The required biasing current of 2500 Ampere is supplied to the cavity via 8 m long coaxial copper feeder. The final stage of the bias current controller uses 28 water-cooled high power transistors connected in parallel as a grounded-emitter configulation. The automatic tuning is achieved in such a way that the phase difference between grid and anode voltages of the power amplifier is detected and used to control the biasing current. To increase the accuracy and the stability of the tuning system, the programmed signal is added to the output of the phase detector. The ferrite properties are most responsible for the limitation of the bandwidth and thus the response speed of the tuning loop.

Frequency control system

The accelerating frequency control system for the KEK booster is illustrated in Fig.5.

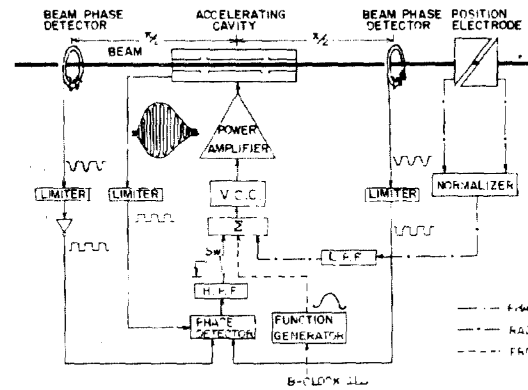


Fig.5 Block diagram of the frequency control system.

The program control and the beam feedback control are combined in the frequency control system. The coarse frequency program is provided in an analogue form by a B-base function generator driven by B-clock pulses. A phase lock that includes the accelerating cavity in the loop was chosen among the different possible ways for the fast beam feedback control. This phase-lock system provides a rapid correction of any non-adiabatic error signals includingin the loop electronics. In order to obtain the pure phase difference between gap phase and phase of the fundamental of the bunch signal, the beam phase information is drived from the two detectors equally spaced at $\pi/2$ radians with respect to the cavity. The phase detector consists of the high speed clipping circuits and a balanced mixer. At the input of the detector, three rectangular pulse shapers provide a further reduction of the amplitude dependence of the detector. A switch (Sw) in Fig.5 contributes to suppress the transient signal at the beam injection. The output signal of the phase detector is fed to the VCO via a high pass filter, so the phase loop corrects only AC variations of the beam-cavity phase difference.

The absolute value of stable phase is controlled by a radial position loop. This radial position servo corrects the static and low frequency errors as those arising from the magnetic field to lock the beam to a fixed radial position. The control system makes it by a pair of electrodes and normalized by an analogue divider. The error signal from the normalizer drives VCO via a low pass filter. This beam control system is possible to use only one oscillator instead of the usual heterodyne system. The output frequency of the VCO is determined by the voltage on a varactor, which is composed of a program term from the function generator and feedback one coming from detections of phase and radial position.

The characteristics of the frequency control system are shown in Table 3.

Table 3

Voltage controlled oscillator	
Tuning range	1.5 to 6.2 MHz
Harmonic content	-30 dB
Maximum error due to nonlinearity	20 KHz
Frequnecy drift	10^{-3}/°C
Residual frequency modulation	5×10^{-5}
Phase detector	
Phase range	-90° to 90°
Gain	0.2 V/radian
Cut off frequency	100 Hz
Bandwidth	100 KHz
Radial position detector	
Position range	-50mm to 50 mm
Gain	15 mm/volt
Bandwidth	250 Hz

Present status of the acceleration

Capture efficiency

The capture efficiency calculated with the voltage program shown Fig.1 was 95 %, however, actually the low efficiency of only 45 % was obtained in the beam survey at the early days of running. Various investigations made clear that the aperture is filled up by the injected beam during the multi-turn injection process, and then, the particles exceeding the aperture due to radial broadening begin to be lost so soon as the injection process is finished and continue to be lost until radial broadening ceases. Then the single turn injection with optimum matching to the injection bump field was tried, and the capture efficiency of 88 % was reached. Fig.6 shows the output voltage of the beam current monitor at the single turn injection and the wave form of the gap voltage, during 2 ms after the injection.

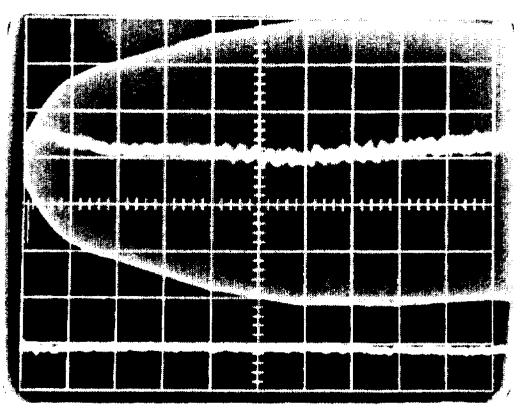


Fig.6 Output signal of a slow beam current monitor and the wave form of the gap voltage. A clattering curve shows the beam current.

When another voltage program that makes the voltage at 1 ms to 7 kV (10.5 kV in the normal case), is used, the capture efficiency goes down to about 70 %, even for the single turn injection, and yet the calculated efficiency is nearly same as one of the normal case. This is a question on the capture process. At present, 55 % capture efficiency is reached under the multi-turn injection.

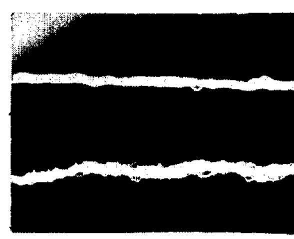
Transmission from 1 ms to the final

The transmission efficiency from 1 ms to the final is 85-90 % under the low beam current (< 3×10^{11} proton/pulse at the final). Various instabilities begin to occur with increase of the beam current and the efficiency lowers to 80 % under the final intensity of 5×10^{11} protons/pulse. The size of RF bucket seems to have some room from a fact that the reduction of transmission was not observed even if the gap voltage after 1 ms was reduced to 87 %, that is, the maximum voltage was reduced to 14 kV from 16 kV.

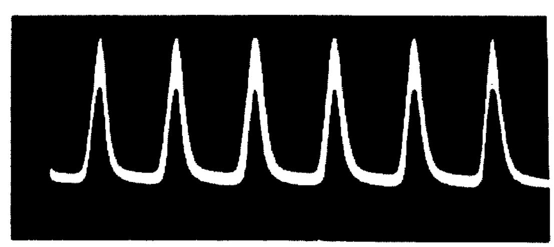
Final stage

At intensities higher than 3×10^{11} protons/pulse, small oscillations of the gap voltage due to beam loading and longitudinal oscillations of the bunch, major parts of which seems to be quadrupole one, are observed at final stage, where the voltage is falling into the extraction voltage, but it is not clear enough whether both oscillations are connected directly with each other or not.

Bunch phase is stabilized to less than ±5° and the radial position is stabilized to 10^{-4} at the extraction period as shown by Fig.7.



Overlapped shots of 20 times. (Intensity 3×10^{11} ppp)



bunch signals from a fast beam current monitor
Overlapped shots of 25 times. (Intensity 2.5×10^{11} ppp)

Fig.7 Beam signals at the final stage.

Reference

1. K. Huke and G. Iwata, "Voltage Programming of Radio Frequency Accelerations in an Alternating Gradient Proton Synchrotron", Japan J. Appl. Phys. 3 (1963) 394.