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KEK FAST CYCLING BOOSTER

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Introduction

KEK 12 GeV Proton Synchrotron aims at the intensity as high as 10^{13} protons/pulse. For instance, a combination of a 50 MeV linac and 8 ∿ 10 GeV separated function type synchrotron with reasonable aperture planned in the early stage of designing gives the space charge limit of 1.8×10^{12} protons/pulse. By inserting a 500 MeV booster synchrotron and replacing with a 20 MeV linac, the incoherent space charge limit of the main synchrotron is raised to 2.0×10^{13} protons/pulse.

The 500 MeV booster is a fast-cycling combined-function type AG synchrotron with a repetition rate of 20 Hz. The mean radius of the booster is 6 m, which corresponds to one nineth of the main ring. Nine beam pulses from the booster every two seconds are stacked into the main ring longitudinally. Synchronization between the RF accelerating systems of the booster and the main ring requires the transition energy of the booster as far as possible from the ejection energy of the booster. Several candidates for the lattice structure of the booster synchrotron were studied[2] and triplet lattice of FDFO was chosen from the view point of the high transition energy.

The first target of the beam intensity delivered by the booster was set at 6×10^{11} protons/pulse, which corresponds to the main ring intensity of 5×10^{12} protons/pulse, and by successive improvement it is hoped that the final goal of the intensity of 1.1×10^{12} protons/pulse will be achieved. In order to realize the final goal the booster should be able to stack the 100 mA linac beam with the emittance of 10 mm mrad in five turns effectively with the efficiency of 80 % and capture as much as 70 % of the beam in the longitudinal phase space. This requires the useful half-aperture of the booster to be 50 mm horizontally and 30 mm vertically. With those aperture the space charge limit in the booster is estimated to be 2.6×10^{12} protons/pulse.

The parameters of the booster synchrotron are given in Table 1.

Table 1 Design parameters of KEK booster

injection field and energy	1.969 kG	20 MeV
maximum field and energy	11.018 kG	500 MeV
mean radius	6.0 m	
betatron oscillation frequency per revolution	$Q_x = 2.2$	$Q_z = 2.3$
accelerating frequency	1.617 - 6.031 MHz	
harmonic number of RF	1	
incoherent space charge limit	2.6×10^{12}	protons/pulse
design intensity	6×10^{11}	protons/pulse
repetition rate	20 Hz	

Guiding field[3]

The booster magnet consists of eight unit magnets with the radius of curvature of 3.3 m. The core of the magnet is made of laminated blocks of oriented low-carbon and low-silicon steel of 0.35 mm thickness, which has been specially developed to obtain a high permeability at high fields. The magnet gap height is 76 mm on the central orbit and the useful half-aperture in horizontal plane is 65 mm. The number of betatron oscillation per revolution is designed to be $Q_x = 2.20$ and $Q_z = 2.30$. In the magnetic field distribution, some amounts of sextupole component are introduced to keep the tune spread due to the momentum error of the particles as small as possible.

One dummy magnet, which is used as a monitor of the magnetic field, is excited simultaneously with the other eight unit magnets on the booster ring by a resonant network with a frequency of 20 Hz. In order to keep the momentum difference of the accelerated particles between those of the booster and the main ring within 2×10^{-4} at the beam transfer, the maximum field of the booster should be stabilized within the limit of 4×10^{-4} in cooperation with the stability of 2×10^{-5} in the accelerating frequency. The maximum and minimum field are stabilized within 2×10^{-4} and 5×10^{-4} respectively.

Observation with beam showed the closed orbit distortion through the acceleration less than 4 mm in the

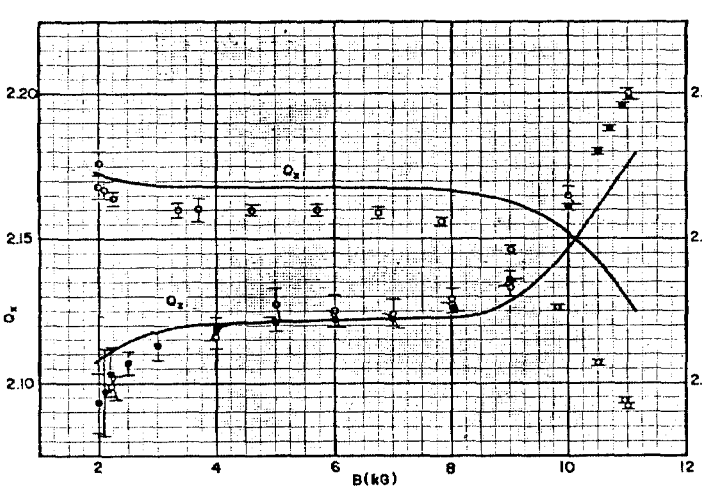

Fig.1 Tune and tune spread at various field levels. Solid curve is from the data of field measurement, and closed and open circles are obtained by RF knockout and Q-meter respectively. Tune spread is denoted with bar.

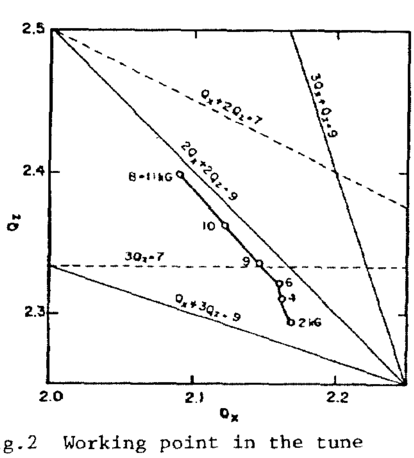

Fig.2 Working point in the tune diagram

horizontal and 3 mm in the vertical plane without any devices for correcting the field fluctuations. The tune and its spread at various field levels are shown in Fig.1, where solid curve is the tune estimated from the data of the magnetic field measurements in comparison with those observed with the accelerated beam by RF knockout method and with a Q-meter[4]. Fig.2 shows the tune shift through the acceleration period. The operation point crosses a resonant line $3Q_z = 7$ at around 9 kG on the excursion during the acceleration. However the seventh harmonic of the sextupole field, which is responsible for exciting the third resonance, is expected to be sufficiently small in the booster magnet with a super-period of 8. In fact, we have no evidence of the excitation of such a resonance.

Injection and ejection system

The injection scheme is so-called multi-turn injection and is performed by locally distorting the closed orbit with two bump magnets. The positions of the bump magnets are one quarter wave length upstream and downstream from the septum inflector. During the injection the bump field is monotonously decreased from its maximum value to zero. The process takes several μsec within the linac pulse of 15 μsec. The numerical calculation for the 10 mm mrad normalized emittance of the linac beam shows that the desirable horizontal emittance shape of the injected beam at the septum magnet is an ellipse with $\alpha = 0$ and $\beta = 2$m while the acceptance shape at the center of the straight section of the booster is $\alpha = 0$ and $\beta = 3.4$ m with the 50 mm useful half-aperture. The number of effective injection turns is expected to be 5 ∿ 6.

Recently, the linac has been operated in routine at the current level of more than 100 mA by the improvement of ion source[5], of which the beam current of about 80 mA is transported to the entrance of the septum magnet. At the instant of 20 μsec from the beginning of the injection, in which the injection process will be almost finished, the maximum captured beam current of 500 mA has been achieved. This circulating current in the booster corresponds to 1.9×10^{12} protons or the number of effective turns is 6.7. In usual operating condition, the captured beam current is 350 ∿ 450 mA for injected beam with the 90 % intensity-including emittance of 6 mm mrad. Fig.3 shows the number of the effective turns captured in the ring for the injected beam current.

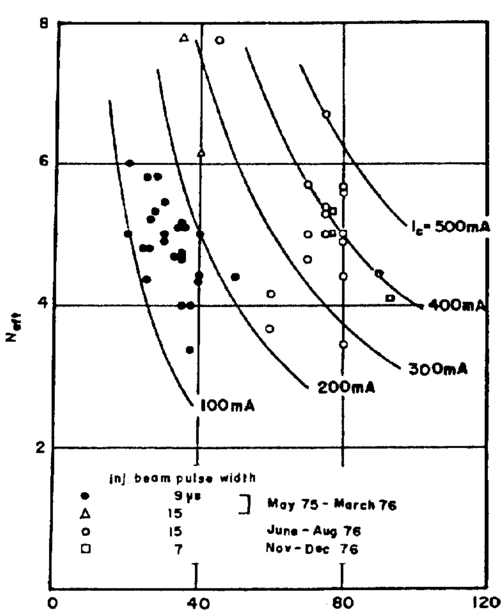

Fig.3 Multi-turn injection efficiency.

The fast extraction of the beam is done by fast kicker in cooperation with bump magnets. The extraction efficiency was confirmed to be 100 % within an error of 5 % with the circulating beam current of 2×10^{11} protons/pulse. The horizontal and vertical emittance of the extracted beam was 59 and 15 mm mrad respectively. These emittances are well within the designed values of the main ring acceptance, $\varepsilon_x = 80$ mm mrad and $\varepsilon_z = 20$ mm mrad[6].

RF accelerating system[7]

RF accelerating system of the booster should operate in a wide frequency range of 1.6 to 6.0 MHz with a high repetition rate of 20 Hz. Moreover, the accelerating frequency is required to be kept constant with the stability of 2×10^{-5} during the beam transfer of nine bunches to the main ring. Various parameters associating the system are shown in Fig.4.

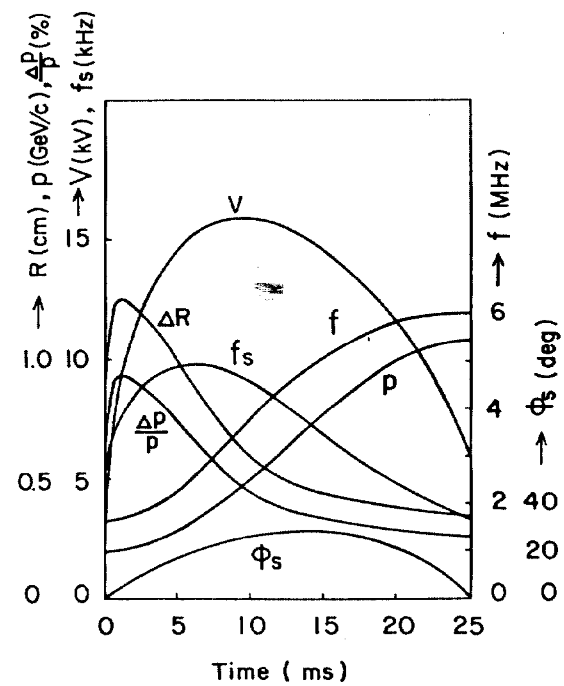

Fig.4 Parameters of RF accelerating system.

The RF voltage program was determined from the results of the calculation on trapping efficiency around injection, bunch shape and phase oscillation throughout the acceleration period. The minimum amplitude of RF voltage required for accelerating the beam without loss is approximately sinusoidal envelope reaching to the peak of about 11 kV at around 12 ms. However, the RF system is designed to yield at least 16 kV in consideration of various possible causes of instabilities in the acceleration. At the final stage of the acceleration, the phase spread of bunch should be about 140° in consideration of the kicker rise time of 80 nsec while high RF voltage bringing about a narrow phase spread of bunch leads to a large momentum spread of the beam. The RF voltage of 6 kV at the end of the acceleration gives rise to the bunch 143° wide in phase and ±0.3 % in momentum spread, which requires the accelerating voltage of 90 kV in the main ring to match the bunches transferred to the ring.

The circulating beam current in the booster is characterized by a minimum at around 1 msec after injection. The beam current captured by the multi-turn injection decreases monotonously to the minimum, where the momentum gain of the injected beam is about 2 %, and then increases with the revolution frequency of the beam. A small amount of beam loss takes place during the acceleration period from 1 msec to the maximum energy. The trapping process of the beam into the RF bucket is considered to be finished at 1 msec. It was tried to improve the RF trapping efficiency with various waveforms of the accelerating voltage envelope. With the injected beam filling the full aperture of the ring, the RF voltage reached to 10.5 kV at 1 msec, which was appreciably higher than the designed one of 7 kV, and the trapping efficiency of the beam into the RF bucket is estimated to be 55 % at maximum.

Beam diagnostic system and vacuum system

Beam diagnostic system is composed of several kinds of beam monitors and some supplemental equipments, e.g., beam scraper, RF knockout electrodes, fast kicker magnet etc. The intensity monitor for the circulating beam makes use of current transformers with wound permalloy tape of 50 μm thickness for the observations of the beam current through the acceleration in slow response and for the bunch-to-bunch intensity measurements in fast response. The observation of the beam position and the radial beam position feedback are carried out with ordinary electro-static pick-up electrodes distributed in several places on the ring. In addition to a tungsten wire monitor set in front of the injection septum, which makes a survey of the injection process, a non-destructive residual-gas ionization monitor[8] is in use for observing the beam profile through the acceleration period. Plastic scintillators are used in case of need as the beam loss monitors. It is necessary for some of those monitors to improve their reliability and accuracy.

Because of the high repetition rate of the guiding magnetic field, the vacuum tube should be considerate of the eddy current induced in itself. In order to reduce the eddy current, a corrugated stainless-steel vacuum tube has been developed, whose electric resistance is equivalent to that of a straight pipe with thickness of 0.03 mm. And also a special metal gasket has been developed, which reduces remarkably the sealing force of flanges to get complete vacuum tightness. Evacuating system is composed of a 160 ℓ/sec and six 1,000 ℓ/sec sputter ion pumps, a 70 ℓ/sec turbomolecular and a 900 ℓ/min rotary pump. The whole vacuum system is successfully operated in the range of 10^{-7} to 10^{-6} torr and no distinct pressure rise has been found with circulating beam.[9]

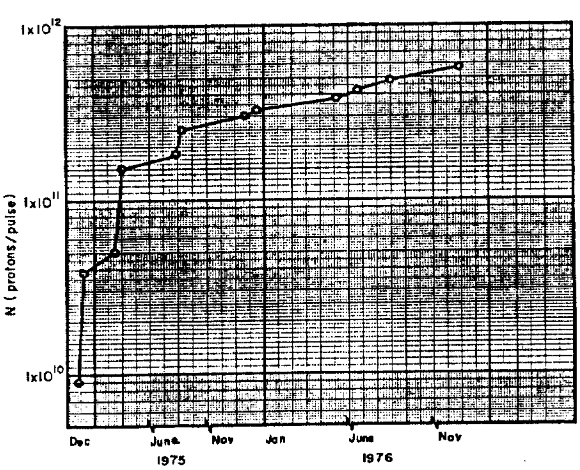

Fig.5 Evolution of the beam intensity in KEK booster.

Present status and future plan

The construction of the booster started in April 1971 and its running-in was taken up in the fall of 1974. In December 1975 the booster delivered the first beam to the main ring. The beam intensity has been steadily increased as shown in Fig.5. The maximum beam intensity we have achieved in this two-years operation is 5.7×10^{11} protons/pulse without any correction devices for the guiding field, which is very close to the first target of the intensity of 6×10^{11} protons / pulse. The transmission of the captured beam by the multi-turn injection to the maximum energy is about one third. The major part of the loss takes place up to 1 msec after injection. Recently, it was found that the remaining beam loss was mainly due to a coherent beam instability induced by the kicker magnet-to-beam interaction around 17 msec or 9 kG. The present performance is summed up in Table 2.

Table 2 Present performance of KEK booster

max. beam intensity achieved	5.7×10^{11} protons/pulse
	1.1×10^{13} protons/sec
emittance of extracted beam	ε_x = 59 mm·mrad
(at 2×10^{11} protons/pulse)	ε_z = 15 mm·mrad
momentum spread	±0.3 %

A new RF cavity is being installed in the booster ring and will be in operation soon together with the old one. In addition to the 500 MeV beam line to the main ring, a new line from the booster is under construction, which is for various fields of researches such as neutron diffraction experiments, pion and muon physics, intermediate nuclear physics, radio-chemistry and cancer therapy.

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