Design of 8-GeV Rapid-Cycle Booster Synchrotron for the KEK B-Factory

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Abstract

An 8-GeV rapid cycle booster synchrotron was designed as possible injector for the KEK B-Factory.

I. INTRODUCTION

We should have an injector to supply 8 GeV electron beams to the high-energy ring (HER) of the KEK B-Factory[1]. Constructing a rapid-cycle booster synchrotron is an attractive option, since this scheme enables us to accelerate electrons to 8 GeV rather easily. Positrons will be injected directly into the low energy ring of the B-Factory; moderate upgrading of the present 2.5 GeV linac to 3.5 GeV is necessary. According to the two options of the KEK B-Factory**, (1) to dig a new tunnel of 1.5 km circumference and accommodate two rings in this tunnel, or (2) to install the two rings in the existing TRISTAN tunnel, the size of possible booster synchrotrons becomes different. In the former case half of the booster is placed in the B-Factory tunnel, while the other half in a bypass tunnel (see Fig. 1); the total length of the booster is 1071.6 m (long booster). In the latter case the booster is accommodated in a special tunnel of 600 m circumference (short booster), since the TRISTAN tunnel (3000 m circumference) is too large for the booster.

Required parameters of the booster are:

injection energy	3.5	GeV
extraction energy	8.0	GeV
repetition rate	50	Hz
intensity	10^{10}	electrons/bunch

The booster is operated in a single-bunch mode. The parameters of the injected beam from the linac are:

transverse emittance	1.5×10^{-7} m
energy spread	2.5×10^{-3}
bunch length	a few mm

Below we mainly consider the long booster.

II. LINEAR LATTICE

A. Long Booster

The booster has two-fold symmetry and two long (60 m) straight sections. One of the straight sections is used for RF stations and the other for injection and extraction. The magnetic lattice for the long booster consists of two arcs, four dispersion suppressors and two long straight sections. The betatron tune is 16.33. One arc cell consists of one F-type and one D-type combined function magnets. Dispersion suppressors are located between arcs and straight sections to match the dispersion function. Each dispersion suppressor has two quadrupole lenses; one of which is shifted from its periodical position in order to suppress beatings of the ß-function. Phase shift of one cell in arcs and in dispersion suppressors is 60 degree. Nine quadrupole magnets in a straight section are placed at the periodical position. Their strength is symmetrical with respect to the center of the straight section. The phase shift of a cell in the straight section is chosen to be 90 degree in order to avoid the intrinsic resonance of the sixth order excited by the fifth-order non-linearity and to suppress beating of the ß-function in the straight sections.

Combined-function lattice results in antidamping in the horizontal direction. Due to the large bending radius of magnets, the growth of the horizontal emittance during acceleration is tolerable (see Fig. 3).

The advantage of the combined function type lattice is that most part of arcs are occupied by combined-function magnets with a small cross section. Whole magnet can be inclosed in a vacuum vessel; this further reduces the cross section of the magnet because the gap of the magnet can be reduced by the thickness of vacuum chamber wall.

Lattice of the final part of the arc, the dispersion suppressor and the straight section is shown in Fig. 2.

B. Short Booster

The magnetic lattice of the short booster is in principle the same as that of the long booster; however, the use of combined-function magnets for arcs is precluded since antidamping nature of the lattice would result in too large horizontal emittance for the B-Factory. Only separated function lattice can be employed in this case. Parameters of both boosters are given in Table 1.

III. COHERENT INSTABILITIES

A. Impedances

The main source of the longitudinal impedance is steps at the entrance and exit of the combined-function magnets where the aperture changes. The impedance of the step Z_{step} is given by

$$Z_{step} = \frac{Z_0}{\pi} \ln \frac{b}{a} \quad ,$$

where Z_0 is the impedance of vacuum, and a and b are the vertical aperture of the magnet and that of the beam pipe between magnets[3]. The total impedance $|Z_{11}/n|$ of the ring becomes,

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** The design has been converged to that based on existing TRISTAN. Two rings will be installed in the TRISTAN tunnel. The 2.5 GeV linac will be upgraded to 8 GeV instead of constructing a booster. See Ref. [2].

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$$\left|\frac{Z_{11}}{n}\right| \sim \frac{2NZ_{step}}{R/a} ,$$

where N is the number of magnets in the ring and R the average radius of the ring. If we substitute $a = 1.5 \times 10^{-2}$ m, $b = 0.15$ m, $N = 190$, $R = 170$ m, we get $|Z_{11}/n| = 9.3\ \Omega$. Taking into account the presence of other impedance sources, we take 10 Ω as the total impedance. Transverse impedance is estimated to be 16.6 MΩ/m by the use of the formula,

$$|Z_\perp| = \frac{2R}{a^2}\left|\frac{Z_{11}}{n}\right| .$$

B. Longitudinal Microwave Instability

The threshold for this instability is given[4] by

$$N_b \le \frac{(2\pi)^{3/2}\frac{E}{e}\sigma_p^2\,\sigma_z\,\alpha}{e\,c\left|\frac{Z_{11}}{n}\right|} .$$

where N_b is the number of particles in a bunch, E the beam energy, e the electron charge, σ_p the energy spread of the beam, σ_z the bunch length, and α the momentum compaction factor.

By substituting the values at injection and extraction given in Table 1, we get $N_b < 1.2 \times 10^{11}$ (at injection) and $N_b < 1 \times 10^{10}$ (at extraction).

The longitudinal microwave instability may appear near the end of acceleration; however, this instability only increases the longitudinal emittance and does not cause any particle losses.

C. Head-Tail Instability

The tune shift and the growth rate of the lowest head-tail (synchrobetatron) mode can be approximated in a frame of the broadband resonator model by the following expressions[5]

$$\Delta\nu = \frac{e R^2 I_B |Z_\perp|}{4\sqrt{2}\,\nu\,E\,\sigma_z} , \quad \frac{1}{\tau} = -\frac{e c^2 I_B |Z_\perp|\,\xi}{4\sqrt{2}\,\alpha\,E\,\omega_{res}\,\sigma_z} ,$$

where I_B is the bunch current, ν = the betatron tune, $\xi = (\frac{\delta\nu}{\nu})/\frac{\delta E}{E}$ the chromaticity, and ω_{res} = the resonant frequency of the broadband resonator ($\omega_{res} = \omega_c$; ω_c is the cutoff frequency). Taking into account that $I_B = eNc/2\pi R$ and $\omega_c = c/a$ and substituting $N_b = 10^{10}$, $|Z_\perp| = 16.6$ MΩ/m, $\alpha = 5.1 \times 10^{-3}$, $\xi = -19$, $\nu = 16.33$, $\sigma_z = 3.3 \times 10^{-2}$ m for E = 3.5 GeV and $\sigma_z = 1.23 \times 10^{-2}$ m for E = 8.0 GeV we obtain

	injection	extraction
$\Delta\nu$	0.02	0.023
τ(ms)	0.523	0.446

The beam intensity is below the threshold of the transverse mode-coupling instability (this instability occurs when $\Delta\nu \simeq \nu_s$, ν_s is the synchrotron tune). On the contrary the head-tail mode (the lowest synchrobetatron mode) is dangerous and has to be suppressed by chromaticity compensation.

For a separated-function lattice chromaticity correction is rather straightforward by adding sextupole magnets. For a combined-function lattice the simplest way is to create an artificial nonlinearity in magnets by making special shape of poles.

IV. TUNE ADJUSTMENT

Tunes are adjusted by changing the strength of quadrupole magnets in the straight sections. Eighteen magnets in the straight sections are grouped into 10 focusing quadrupoles and 8 defocusing quadrupoles. Necessary variation of quadrupole magnet strength for changing tunes by 0.1 is smaller than 5% and beating of the ß-function in the arc is negligible.

V. REQUIRED APERTURE

During acceleration the emittance of the beam varies due to radiation damping, adiabatic damping and quantum excitation. Figure 3 shows this change. Since the emittance is maximum at injection, the required aperture becomes maximum at injection. By assuming that the maximum closed orbit displacement is 10^{-2} m in both directions, we get apertures A_x and A_y shown below.

	F-magnet	D-magnet	Q-lense
A_x	31.2	22.4	15.1
A_y	10.8	15.1	15.1

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

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Table 1 Parameters of the Boosters

	Long Booster	Short Booster	
Injection energy	3.5		GeV
Ejection energy	8.0		GeV
Inj. trans emittance	1.5×10^{-7}		m
Inj. energy spread	2.5×10^{-3}		
Circumference	1071.6	599.2	m
Number of cells	94	70	
Phase shift cell	60°	60°	
Betatron tunes ($\nu_x = \nu_y$)	16.33	11.66	
Superperiodicity	2	2	
Length of period	11.4	8.56	m
Length of straight section	57	42.8	m
Bending magnet			
whole number	162	116	
in main lattice	154	108	
in suppressors	8	8	
length	4.56	2.58	m
k_1*	± 0.0564	0	m^{-2}
k_2* (F magnet)	0.0193	0	m^{-3}
k_2* (D magnet)	0.0264	0	m^{-3}
bending radius	116	43.9	m
Quadrupole lense			
whole number	26	140	
in straight sections	18	18	
in suppressors	8	8	
length	0.6	0.6	m
k_1* (max)	0.455	0.616	m^{-2}
Natural chromaticity	-18.9	-13.0	
Momentum compaction	5.12	10.54	$\times 10^{-3}$
RF frequency	508		MHz
RF Voltage	10	20	MV
Energy loss per turn	3.16	8.96	MV
Damping partition numbers			
T_x	-0.8216	0.9801	
T_y	1.0007	1.004	
T_z	3.8209	2.0195	
Synchrotron tune			
E = 8.0 GeV	0.0401	0.0602	
E = 3.5 GeV	0.0643	0.0965	
Final emittance			
ε_x	11.5	17.7	10^{-8} m
ε_y	4.1	0.59	10^{-8} m
ε_z	0.86	1.75	10^{-8} m
Bunch length			
E = 3.5 GeV	3.2	2.5	cm
E = 8.0 GeV	1.3	2.3	cm
Energy spread			
E = 8 GeV	6.6×10^{-4}	7.6×10^{-4}	

* $k_1 = \left(\frac{\partial B_y}{\partial x}\right)/(B\rho)$, $k_2 = \left(\frac{\partial^2 B_y}{\partial x^2}\right)/(B\rho)$

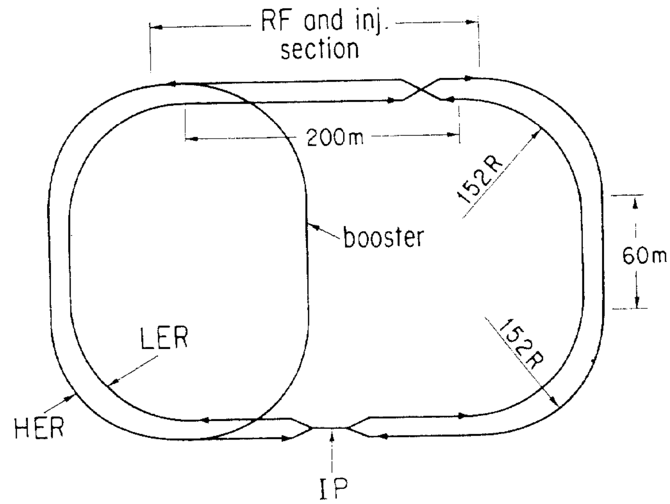

Fig. 1 Layout of booster and B-Factory.

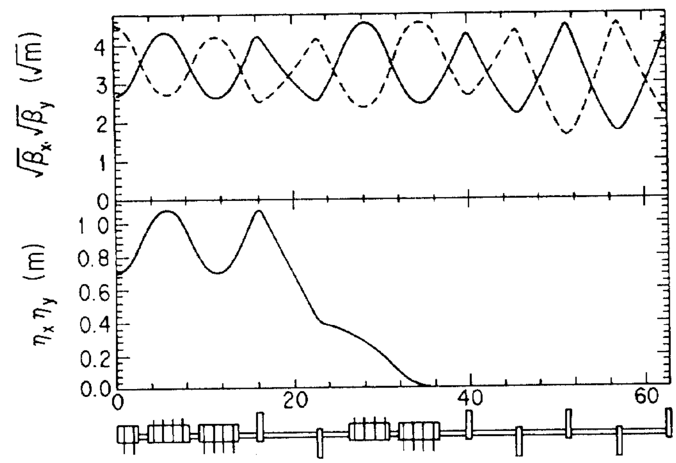

Fig. 2 Lattice of the final part of the arc, the dispersion suppressor and the straight section.

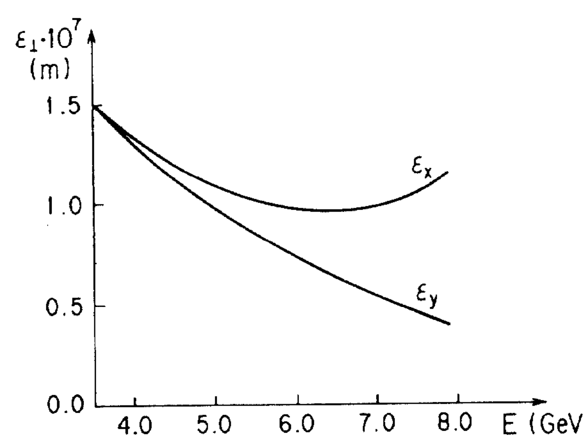

Fig. 3 Change of emittance with energy.