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LATTICE OF PHOTON FACTORY STORAGE RING

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Abstract

The lattice of the storage ring of KEK Photon Factory (dedicated synchrotron radiation source) is described. The design principle is the availability of straight sections for the wiggler and the flexibility of optics. The final design is checked with respect to the disturbance of beam dynamics by momentum error and magnetic imperfections.

Introduction

The Photon Factory is the dedicated synchrotron radiation facility at KEK. The general description of the facility is given by Kikuchi in these Proceedings[1]. The general parameters of the electron storage ring are listed in Table 6 of his paper.

The nominal operating energy is 2.5 GeV. The magnets and their power supply system, however, are so designed as to raise the electron energy up to 3 GeV by changing the field strength slowly after the beam is stacked. The maximum field strength of bending magnets is 11.6 kG. The wiggler magnet as conceived presently is the superconducting three poles magnet. The central magnet is twice as long as the lateral magnets and, therefore, the magnetic fields are all the same to make a zero net beam deflection. It is the so called vertical wiggler, in which the magnetic field direction lies in the horizontal plane[2] Although technical problems such as the beam-stay-clear requirement during injection, cooling of downstream vacuum chamber, etc, must be solved, the usable energy region of emitted light can be extended up to 20 keV or more with the field strength of 6 Tesla. The maximum offset of the beam center line in the wiggler triplet is 10 mm. The synchrotron radiation loss becomes 470 kV per turn, while it is 400 kV without the wiggler. In addition to restoring these energy losses, the two RF accelerator sections must provide an overvoltage in order to insure a useful quantum lifetime. The peak voltage of 2.1 MV is required without the wiggler. A power is supplied by four klystrons, each delivering a cw output power of 180 kW. The RF frequency is 500.03 MHz, the harmonic number being 312[3]

The injection into the storage ring is carried out in the conventional ways; firstly, the multi-turn injection scheme in which a pulse of electron beam as long as 1 μs is injected while the revolution time is 624 ns, and secondly, the single bunch injection scheme in which a short pulse of about 1 ns in duration is deposited into the center of the storage ring RF bucket. The linac is designed to deliver the electron beam of 50 mA with energy spread of 0.2 % and emittance of 0.02π mm.mrad, and to operate in 50 Hz. For technical reasons, however, the injection rate is chosen to be less than 10 Hz. The injection time may then be less than 10 minutes, even if the worst injection condition is assumed. The transport line has the capability of momentum analysis as well as optics matching. The maximum value of dispersion is 5 m, and the separation of 10 mm can be obtained for momentum difference of 0.2 %. With the aid of this momentum slit, it is possible to prevent the electrons with large momentum error from entering into the storage ring injection system.

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Description of lattice

The lattice shown in Fig. 1 is the final design. It consists of two regular arcs and the insertions matched to them.

In designing the storage ring lattice, the following points have been considered.
1. Several medium straight sections, which are longer than 3 m, are necessary to accomodate the injection system, the accelerating cavities, the wiggler magnet and other equipments. Some of them should have zero dispersion, since it is desirable especially at the position of accelerating cavities and wigglers.
2. The relatively long straight sections, say 5 m, are required, which will be useful for installing some special wigglers in the future. The amplitude functions must be adjustable at these long straights. The dispersion function must be vanishing.
3. Enough space for correcting and diagnostic elements must be provided. Position monitors of button type, vertical steering dipoles and sextupoles are items of primary importance. Specifically, we need relevant position for chromaticity correcting sextupoles, since strong sextupole magnets may introduce undesirable momentum dependent non-linear effects.

As shown in Fig. 2 in more detail, the magnet arrangement contains the low-β insertion, the achromatic bend, the straight section with zero dispersion, a dispersion suppressor and normal cells up to the center of the arc, a symmetry point.

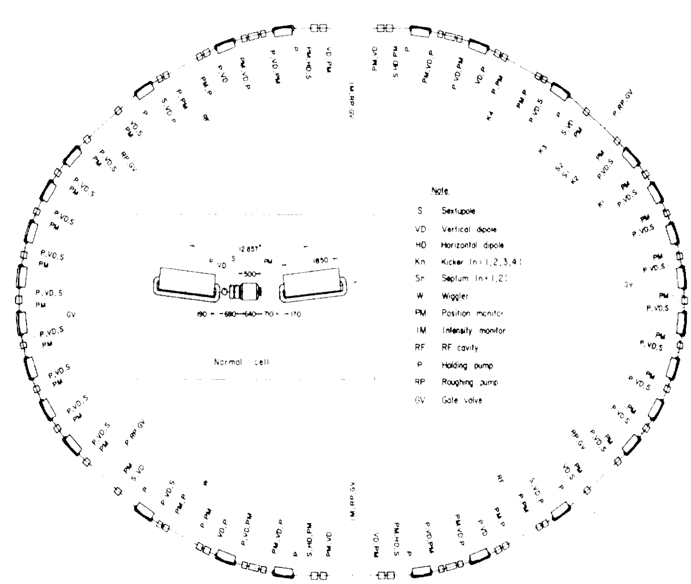

Fig. 1 Lattice of storage ring.

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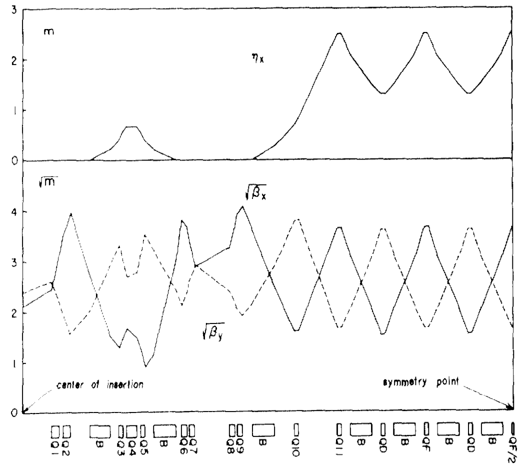

Fig. 2 Betatron and dispersion functions for the standard configuration.

The focusing structure of the normal cell in the regular arc is a FODO configuration. The beta values at the quadrupoles are very different in this case, which is important if one wants correction magnets to act orthogonally. Therefore, a sextupole and a vertical steering dipole are located in the straight section upstream of each quadrupole magnet in normal cells, as shown in the inserted figure in Fig. 1. The horizontal steering is accomplished through the use of trim winding on the bending magnet. In this section is also located regularly a holding ion pump, which will pump out gases desorbed at the radiation mask placed at that location in order to protect a downstream vacuum chamber from being exposed to intense synchrotron radiation. The short straight section downstream of the quadrupole is open for general use except for a position monitor which is regularly located there. Injection kickers, skew quadrupoles, octupoles and others are placed in this section, as needed.

The vacuum chamber for each bending magnet is provided with a radiation port, through which the synchrotron radiation originating at a point 40 cm downstream of the entrance of the magnet is extracted outside. The beam line can accept the radiation extending over 20 mrad.

The dispersion suppression is accomplished by leaving out a bending magnet of the normal cell and modifying the field strength of two adjoining quadrupoles (Q10 and Q11), as shown in Fig. 2. The quadrupole triplet (Q3-Q4-Q5) and two bending magnets constitute the achromatic bend. This guarantees the vanishing dispersion at the low-β insertion. Matching of the amplitude functions can be adjusted by three quadrupole doublets (Q1-Q2, Q6-Q7, Q8-Q9). The free space 5 m long at the center of insertion seems to be adequate for installing special wigglers, such as an undulator and a helical wiggler, in the future.

The amplitude and dispersion functions of one quadrant of the ring are plotted in Fig. 2 for the standard configuration which has moderate values of β_x and β_y at the center of insertion. The betatron tunes are $\nu_x = 6.25$ and $\nu_y = 5.25$. Since flexibility of the optics has been a primary concern in our design, twelve families of quadrupoles are independently powered. Table 1 lists beam parameters for some additional configurations as well as the standard configuration.

The lattice of the standard configuration has a natural chromaticity, $\xi_x = -8.7$ and $\xi_y = -6.3$, which

Table 1 Beam parameters

	Standard configuration	Small emittance configuration	Low-β configuration
ν_x	6.25	7.25	7.25
ν_y	5.25	3.25	5.25
α	0.0348	0.0169	0.0348
ξ_x	-8.72	-15.5	-20.7
ξ_y	-6.31	-6.07	-11.8
τ_x(ms)	8.9	8.9	8.9
τ_y(ms)	7.8	7.8	7.8
τ_ε(ms)	3.7	3.7	3.7
ε_x(mm·mrad)	0.410π	0.172π	0.400π
σ_ε/E	0.71×10^{-3}	0.73×10^{-3}	0.71×10^{-3}
σ_z(cm)	1.94	1.40	1.94
ν_s	0.038	0.026	0.038
β_x^*	4.5	5.8	0.1
β_y^*	5.6	18.5	1.0

originates from the ring quadrupoles. The chromaticity is pushed to higher values in some configurations. Most simply, two families of sextupoles are required to control horizontal and vertical chromaticity. At the location shown in Fig. 1, the strengths of sextupoles are $S_F = 0.22\ m^{-2}$ and $S_D = -0.33\ m^{-2}$ ($S = B''\ell_S/2B\rho$). Since the strong non-linear fields required for chromaticity correction can perturb the linear beam dynamics[4], we have examined the effects for the present lattice. As shown in Fig. 3, the variation of amplitude and dispersion functions is not so large even for the momentum error of 1 %. (Note that the rms energy spread of electrons is 0.07 %). The variation of tunes with momentum is also small; 0.003 for $\Delta p/p = 1$ %. In order to insure the stability of motion for this configuration of sextupoles, we have tracked particles over 10,000 turns, which is about 70 % of a damping time at 2.5 GeV, and found that the stability limit is well outside the beam-stay-clear, as shown in Fig. 4. For the low β configuration, however, the value of β_x for $\Delta p/p = 1$ % becomes twice as large as that for right momentum particle, and it seems that a different sextupole configuration must be examined.

The effect of the higher multipole content in the

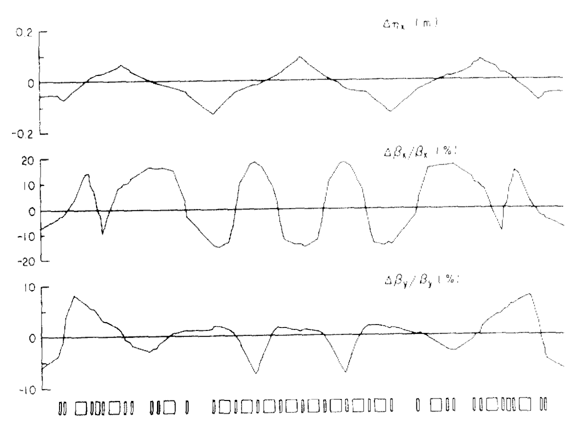

Fig. 3 Variation of the betatron and dispersion functions with momentum error $\Delta p/p = 1$ %. (standard configuration)

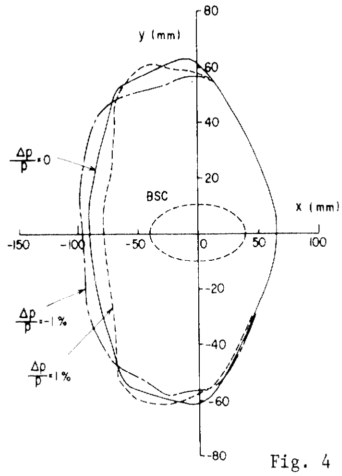

Fig. 4 Stability limit from particle tracking. (standard configuration)

quadrupoles and bending magnets on the particle dynamics has been examined in order to determine the tolerances on the higher pole content in both magnets. Its primary source is the fringe fields, not from the body of magnets, because the quadrupoles and bending magnets in this ring are relatively short. The pole profile and the end correction have been determined with a prototype magnet, and the multipole content of the magnetic field has been measured. Since the effect of sextupole field is compensated by chromaticity correction sextupoles, we have evaluated the betatron oscillation frequencies as a function of the betatron and energy oscillation amplitudes by using multipole components higher than octupole[5]. Based on the field measurements on the prototype magnet, it has turned out that the tune spread is within 0.005 at the most for the particle with betatron and energy oscillation amplitudes ten times as large as the rms values.

For the vertical wiggler conceived presently, its effect on beam dynamics has turned out to be small, since it is placed at the zero η_x location. Increase in energy spread and bunch length is about 20 %. All we have to do is the compensation of optics mismatching arising from introducing the wiggler. This is accomplished satisfactorily by adding two quadrupoles near the wiggler[6].

Aperture requirements

In this design, the beam-stay-clear has been defined as

$$BSC = (10\sigma_{x,y} + C.O.D.),$$

in order to make it possible to achieve the full acceptance without relying on the closed orbit correction. σ_x is the horizontal rms beam width defined by

$$\sigma_x = [\sigma_{x\beta}^2 + \eta_x^2(\sigma_\varepsilon/E)^2]^{1/2},$$

where $\sigma_{x\beta} = \sqrt{\varepsilon_x\beta_x}$ is the rms horizontal betatron oscillation amplitude assuming no coupling. σ_y is the rms vertical betatron oscillation amplitude in the case of the full coupling between horizontal and vertical betatron oscillations. The closed orbit distortions have been calculated assuming the quadrupole alignment error of 0.1 mm, the dipole field error of 0.1 % and the roll error of 0.2 mrad (all these are the rms values). The maximum closed orbit distortion is 27 mm and 11 mm in the horizontal and vertical planes, respectively.

The beam height is actually determined by the horizontal-vertical coupling of betatron oscillations and the vertical dispersion which is ideally vanishing. The latter comes from the non-vanishing vertical closed orbit distortion inside quadrupoles and sextupoles which are placed at finite-η_x positions. The quadrupole roll error associated with finite η_x may contribute to the vertical dispersion but this is usually small. In the same assumption above, the expectation value of maximum vertical dispersion is estimated: $\langle\eta_y\rangle = 0.1$ m. The expected value of the coupling coefficient of the horizontal-vertical coupling can be calculated in the same manner: $\langle Q\rangle = 4.5\times10^{-3}$. Using these figures, the expectation value of the vertical beam size is $\sigma_y = 1.0$ mm. On the other hand, the rms vertical betatron oscillation amplitude assuming full coupling is $\sigma_y = 1.7$ mm. Since in experiences on existing storage rings they have found occasionally a strong coupling which reaches about 100 % for large betatron amplitudes, we have adopted the assumption of full coupling and chosen the vertical beam-stay-clear to be 60 mm in the quadrupole magnet and 52 mm in the bending magnet.

In determining the beam-stay-clear in the horizontal plane, it is necessary to take account of the room for injected beams to circulate around the bumped orbit during the injection process. Resultantly, the required half aperture is 75 mm in the quadrupole magnet and 60 mm in the bending magnet. For ensuring the quantum lifetime, 60 mm and 50 mm are sufficient in the quadrupole and dipole magnets, but it seems to have a beneficial effect at very little extra cost to add 10 to 15 mm to the horizontal aperture for all magnets, although magnets which need large aperture are localized only around the injection point.

Since the bending magnet is a straight magnet made of solid core for simplicity and economical reasons, sagitta of 50 mm must be taken into account in the horizontal useful aperture of the bending magnet. The actual gap of the magnet must also include an additional allowance for aluminum vacuum chamber walls (2×6 mm), a thermal shield for bake-out and installation tolerances. The useful aperture of the bending magnet, therefore, has been 70 mm and 170 mm in vertical and horizontal directions, respectively.

Although the beam has a very different aspect ratio at F and D quadrupoles, the cross sections of vacuum chambers are identical for both magnets. The inscribed bore radius is 55 mm except for the triplet quadrupoles in the achromatic bend, in which it is 45 mm.

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