Model Calculations of Optics for the SPring-8 Storage Ring

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1. Introduction

During the commissioning of the SPring-8 storage ring, measured values of betatron tunes were found to be smaller than calculations in both horizontal and vertical directions. Since similar discrepancies were observed for three typical optics with different operation points, this seemed to be systematic. We then tried to explain these discrepancies by introducing various factors which were not taken into account in our design calculations. In the following we give a report on these factors and describe how we have improved the model. We will see that the improved model can give better values to the betatron tunes.

2. Corrections to Optics Calculations

In the design calculation mentioned above, all magnets were assumed to have required strengths with design values of the effective length. As pointed out, this model overestimates the betatron tunes in both horizontal and vertical directions and needs to be improved. For this, we took account of the following correction factors in the model:

2.1. Focusing due to Sextupole Field Component at Each Edge of Bending Magnets

The bending magnet in the SPring-8 storage ring is of rectangular type with the effective length of 2.804m and the bending angle of 2π/88. In addition to the nominal dipole field, the strength distribution of higher multipole fields were measured by using the Hall-probe[1]. From these data we found that a sextupole field component at the edge is not negligible in calculating optics. This is because bending magnets were aligned so that a stored beam passes through a good-field region on the average in the inside of the magnet, and the orbit position at the edge is shifted by 12.5mm in the horizontal direction as shown in Fig. 1.

Stored electrons then feel an additional quadrupole field at each edge of bending magnets and this field acts as a horizontally-focusing quadrupole magnet. The integrated strength of this field along the orbit was

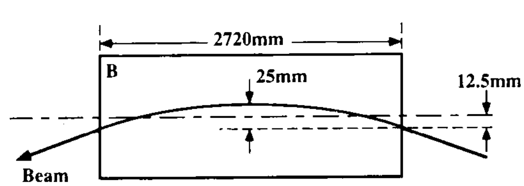

Fig. 1. A schematic drawing of the orbit in the bending magnet.

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obtained to be 0.0174[T] per edge. Since there are 88 bending magnets in the ring, the total strength is 3.06[T], which is comparable to the strength of the weakest one quadrupole magnet in the ring. Remembering that (1) a quadrupole field error causes the optics distortion proportional to the betatron function at that point and (2) in the SPring-8 storage ring the vertical betatron function is larger than the horizontal one at each edge of bending magnets, we can expect that the vertical tune will be reduced significantly but the horizontal tune will not be affected so much. Numerical results will be shown later (see Table 3).

2.2. Strength Reduction of Quadrupole Magnets due to Nearby Steering Magnets

In the SPring-8 storage ring there are ten families of quadrupole magnets Q1, Q2, ... and Q10 in one unit cell and some of these are settled close to steering magnets. Then, a part of magnetic flux from such a quadrupole magnet will be absorbed to the yoke of a nearby steering magnet, and consequently the integrated strength will be reduced. Since main and steering magnets are settled periodically, this reduction will occur in a systematic way.

We had measured the reduction factor due to this effect before the magnet alignment[1]. The results showed that the integrated strength of Q2 and Q9 will be reduced by about 0.085% and that of Q5 and Q6 will be reduced by about 0.17%. Since Q2, Q9, Q5 and Q6 are all horizontally-focusing quadrupole magnets and the betatron function takes a large value in the horizontal direction at these magnets, we can expect a significant reduction of the horizontal tune. In optics calculations we took account of this effect by reducing the effective length, and hence the integrated strengths, by the factor given above.

2.3. Use of Measured Effective Lengths of Quadrupole Magnets

Though the core lengths of quadrupole magnets were adjusted in fabrication so that the effective length becomes as close as possible to design values, we found that measured effective lengths were longer than designs. For example, the effective length of Q1, Q2, ... and Q10 for a typical "hybrid" optics (see the next section) was measured and found to be longer than design values by 2.5%, 0.7%, 1.5%, 1.2%, 0.6%, 0.5%, 1.2%, 0.9%, 0.0% and 2.1%, respectively[1]. We improved the accuracy of optics calculations by incorporating measured values of the effective length. Note that though the effective lengths were tuned, the integrated strengths $B'l$ were kept unchanged in calculations. This is because power supplies were calibrated so that integrated strengths are generated as required. The correction due to this will be small when compared with previous two factors but non-negligible in our discussion.

In calculating optics we also took account of a slight dependence of the effective length on magnet strengths on the basis of field measurements.

2.4. Correction of Energy Scaling of Quadrupole Magnets in the Arc Section

Since the dispersion function is localized in the arc section by using four (actually two by symmetry) families of quadrupole magnets Q4, Q5, Q6 and Q7, we can calibrate the energy-scaling factor for these magnets by measuring a systematic leakage of the dispersion function. We determined correction factors by using a "hybrid" optics and searching the best strengths to minimize the leakage of a measured dispersion function. The results showed that when compared with the strength of bending magnets, the relative strength of Q4 and Q7 is weak by a factor 0.9990 and that of Q5 and Q6 by 0.9985.

3. Numerical Results

To check our model, we applied it to the three kinds of low-emittance optics: "hybrid", "high-beta" and "high-tune" optics. Original design values of the natural emittance for these optics are 7.0, 7.0 and 5.5nmrad, respectively, and betatron functions are drawn in Fig. 2.

By using the improved model with all corrections included, we obtained betatron tunes as listed in Table 1. For comparison, we also list calculated tunes without corrections together with measured values. The accuracy of the tune measurement is better than 0.01. In these calculations, actual set-values in the operation were used for the quadrupole magnet strengths: in calculations there are no free parameters that are used for fitting. We can see that the agreement between calculations and measurements has been improved for all optics in both horizontal and vertical directions. This fact indicates that our correction scheme works well.

In Table 2 we list the natural emittance calculated by the improved model. Also listed is the calculated r.m.s. leakage of the dispersion function outside of the arc section. Note that in the actual operation of the "high-beta" and "high-tune" optics, we have not yet performed fine-tuning of the strength of the quadrupole magnets to minimize the leakage of the dispersion function as explained in section 2.4. This is the reason why we obtain a larger dispersion function for these two optics compared with the "hybrid" optics in the model calculation. This will be checked in future studies.

In the previous section we listed four kinds of correction factors that should be included in the model calculations. By applying each correction to the original model one by one and comparing the results, we can check how much is the effect of each correction. The results are summarized in Table 3, where the change of the betatron tune and the betatron function caused by each correction are shown.

4. Discussions

We could obtain improved results for betatron tunes by incorporating correction factors in the model. However, there still seems to be some discrepancies between calculations and measurements. Parts of these will originate in other unknown factors.

One possibility will be the energy-scaling factor of quadrupole magnets in the outside of the arc section (Q1, Q2, Q3, Q8, Q9 and Q10), since these factors were set to unity in calculations. The effect of this can be estimated by changing their values from unity and calculating betatron tunes. We performed such calculations by assuming a unique value for these factors. For example, if we use a factor of 1.0005, we obtain betatron tunes of (51.225, 16.367), (42.191, 15.317) and (53.320, 20.467) for the "hybrid", "high-beta" and "high-tune" optics, respectively. These results indicate that if we use a suitable set of the energy-scaling factors (which should be determined experimentally by some means), the overall agreement

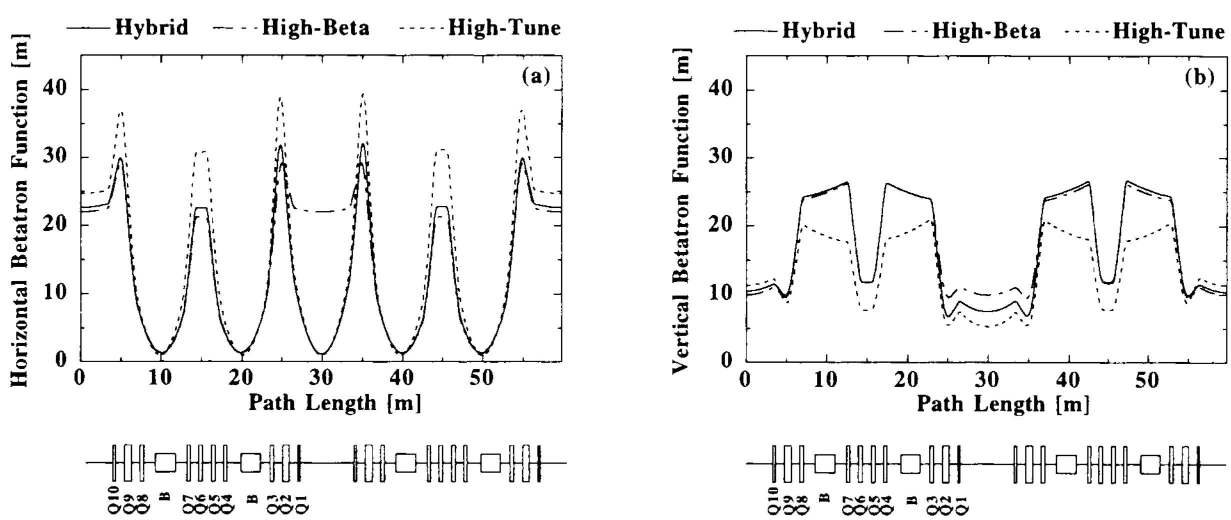

Fig. 2. (a) Horizontal and (b) vertical betatron functions for "hybrid", "high-beta" and "high-tune" optics calculated with the improved model with all corrections included.

can be improved for all optics. Further studies are necessary for this.

We should also mention here the effect of closed orbit distortion (COD) at sextupole magnets, which will generate optics distortions. For the "hybrid" optics we monitored tune values during COD corrections but could not found remarkable variations. So, this effect is too small to explain the remaining discrepancies but needs to be checked for other optics. Computer simulations with alignment data of magnets will also be helpful for understanding and improvement of the optics. These will be studied in the future.

References

[1] J. Ohnishi, unpublished note.

Table 1. Horizontal and vertical betatron tunes (ν_H, ν_V) for three different optics: calculations ($\nu_H^{(calc)}$, $\nu_V^{(calc)}$) and measurements ($\nu_H^{(meas)}$, $\nu_V^{(meas)}$).

	Hybrid Optics	High-Beta Optics	High-Tune Optics
($\nu_H^{(calc)}$, $\nu_V^{(calc)}$)			
with corrections	(51.187 , 16.356)	(42.167 , 15.308)	(53.270 , 20.454)
without corrections	(51.459 , 16.542)	(42.407 , 15.498)	(53.614 , 20.590)
($\nu_H^{(meas)}$, $\nu_V^{(meas)}$)	(51.24 , 16.31)	(42.20 , 15.28)	(53.23 , 20.35)

Table 2. Calculated natural emittance $\varepsilon^{(calc)}$ and the r.m.s. leakage of the dispersion function $\Delta\eta^{(calc)}$ outside of the arc section.

	Hybrid Optics	High-Beta Optics	High-Tune Optics
$\varepsilon^{(calc)}$ [nmrad]	7.10	7.05	5.78
$\Delta\eta^{(calc)}$ [cm]	0.13	0.88	0.67

Table 3. The change of the betatron tune ($\Delta\nu_H^{(calc)}$, $\Delta\nu_V^{(calc)}$) and the betatron function ($\Delta\beta_H^{(calc)}$, $\Delta\beta_V^{(calc)}$) caused by the corrections explained in the text. In the table these corrections are denoted by C1, C2, C3 and C4:

C1: "Focusing due to Sextupole Field Component at Each Edge of Bending Magnets"
C2: "Strength Reduction of Quadrupole Magnets due to Nearby Steering Magnets"
C3: "Use of Measured Effective Lengths of Quadrupole Magnets"
C4: "Correction of Energy Scaling of Quadrupole Magnets in the Arc Section"

	Hybrid Optics	High-Beta Optics	High-Tune Optics
($\Delta\nu_H^{(calc)}$, $\Delta\nu_V^{(calc)}$)			
by C1	(+0.029 , -0.230)	(+0.029 , -0.227)	(+0.032 , -0.175)
by C2	(-0.178 , +0.086)	(-0.151 , +0.081)	(-0.241 , +0.064)
by C3	(-0.058 , -0.039)	(-0.057 , -0.042)	(-0.045 , -0.025)
by C4	(-0.068 , -0.001)	(-0.064 , -0.002)	(-0.093 , -0.001)
($\Delta\beta_H^{(calc)}$, $\Delta\beta_V^{(calc)}$) [m] (r.m.s. value)			
by C1	(0.01 , 0.59)	(0.01 , 0.51)	(0.06 , 0.34)
by C2	(0.24 , 0.09)	(0.35 , 0.10)	(0.57 , 0.08)
by C3	(0.11 , 0.05)	(0.11 , 0.05)	(0.15 , 0.07)
by C4	(0.13 , 0.004)	(0.20 , 0.004)	(0.24 , 0.005)
($\Delta\beta_H^{(calc)}$, $\Delta\beta_V^{(calc)}$) [m] (maximum absolute value)			
by C1	(0.04 , 1.33)	(0.03 , 1.06)	(0.24 , 0.84)
by C2	(0.86 , 0.23)	(0.60 , 0.21)	(1.77 , 0.17)
by C3	(0.28 , 0.16)	(0.21 , 0.11)	(0.53 , 0.17)
by C4	(0.53 , 0.01)	(0.36 , 0.01)	(0.89 , 0.01)