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Suppressing the *X–Y* coupling effect in compact electron storage rings

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The x–y coupling effect, especially the tilt of the beam profiles, in the Super-ALIS compact electron storage ring has been effectively eliminated. The main feature of this method is the suppression of the most harmful Fourier components of the skew-quadrupole perturbation by using just one thin skew-quadrupole magnet. Therefore, the method should be simple and effective for coupling suppression in compact storage rings that have little space for correction instruments.

Keywords: storage rings; coupling; sextupole fields; closed-orbit distortions; skew-quadrupole magnets.

1. Introduction

In storage rings for synchrotron radiation the sextupole magnetic field exists as a stray field in the bending magnets (BMs) or sextupole magnets for chromaticity correction. It is known that, as well as the original sextupole perturbation, beams passing through a vertical off-centred orbit also experience a skew-quadrupole perturbation. The skew-quadrupole perturbation couples the horizontal and vertical motion of the beams and generally results in the tilting of beam profiles (Peggs, 1983). Such tilted beam profiles are undesirable for experiments using synchrotron radiation.

In recently developed compact storage rings (Hosokawa *et al.*, 1989; Jordan *et al.*, 1989) the problem has become more serious because most of these compact rings use superconducting bending magnets that generally have a large sextupole field. Moreover, in superconducting compact storage rings, the closed-orbit distortion is likely to be larger.

A serious coupling effect was also observed in the Super-ALIS superconducting compact storage ring (Yamada *et al.*, 1996), and the quality of synchrotron radiation beams was degraded. In this work we present a method for coupling reduction that is suitable for compact rings. Then we confirm the validity of this method, both *via* simulations and *via* experiments with Super-ALIS.

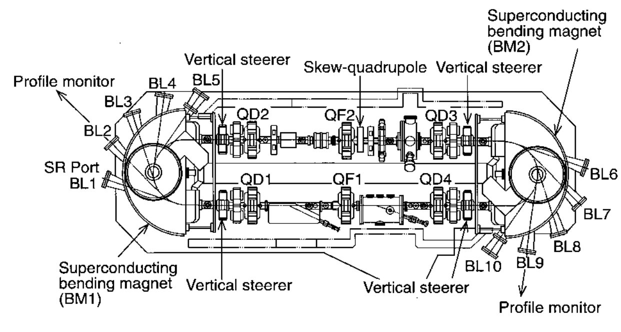


Figure 1
The superconducting storage ring Super-ALIS.

Table 1
Super-ALIS machine parameters.

Maximum energy	600 MeV
Maximum bending field	3.0 T
Type of BMs	Superconducting (with iron core and yoke)
Betatron tune	$Q_x = 1.585$, $Q_y = 0.583$
Transverse emittance	$9.5 \times 10^{-7}\pi$ m rad
Circumference	16.8 m

2. Review on the method for coupling reduction

In our previous work (Yamada & Hosokawa, 1997) we have shown an important characteristic that the coupling effect appears only when the wave number of the azimuthal distribution of the skew-quadrupole perturbation is close to the difference in the horizontal and vertical tunes. This result gives an effective method for coupling reduction. The coupling effects can be greatly reduced by suppressing only the Fourier components $g_{\pm k_d}$, where k_d is a natural number close to the absolute value of the tune difference. The method can generally be implemented by adding two thin skew-quadrupole magnets because the Fourier components to be suppressed are those with wave numbers $+k_d$ and $-k_d$.

The number of additional magnets can be reduced to just one. The solution is that a thin magnet with strength $-\pi f_{k_d}$, where $f_{k_d} = 2(g_{k_d} g_{-k_d})^{1/2}$, is located at a position where the perturbation of the k_d component originating from the undesirable skew-quadrupole force is maximum (Yamada & Hosokawa, 1997). A solution can be that a πf_{k_d}-strength magnet is located at a position where the undesirable skew-quadrupole force is minimum.

It is a great advantage for compact rings that only one or two magnets are enough for coupling reduction because compact rings have little space for additional instruments.

3. Coupling behaviour in Super-ALIS

3.1. *Super-ALIS and the source of the coupling*

Super-ALIS is a superconducting electron storage ring for synchrotron radiation (Hosokawa *et al.*, 1989). A schematic drawing of this machine is listed in Fig. 1 and the machine parameters are listed in Table 1. This machine has two super-

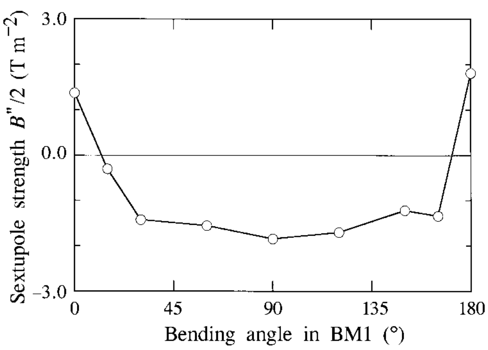


Figure 2
Sextupole components of BM1 along the designed central orbit.

conducting 180° bending magnets, BM1 and BM2. The magnets have a maximum magnetic field of 3.0 T. The uniformity of the field is not much better than that of normal-conducting magnets; therefore, sextupole fields in the BMs are not negligible for beam motions.

Fig. 2 shows the measured sextupole components along the designed orbit when the field of BM1 is 3.0 T. The sextupole component $\partial^2 B_y/2\partial x^2$ is about -1.8 T m^{-2}, except at the edges where the sextupole components show values nearly inverse to those of the centre of the BM.

When vertical orbits are displaced in these sextupole fields, skew-quadrupole perturbations are produced and *x–y* coupling effects arise.

3.2. *Estimation of the skew-quadrupole perturbation*

To estimate the coupling effect originating from the vertical closed-orbit distortion in the sextupole field of BMs, we assume the closed orbit observed in the routine operation of Super-ALIS 600 MeV storage. The orbit distortion is shown in Fig. 3. The orbit is that requested by synchrotron radiation users because it gives a level median plane for beamlines; however, it gives about ±1.5 mm displacements from the median plane of the BMs. The difference in the median planes might arise from the uneven sinking of the storage ring floor.

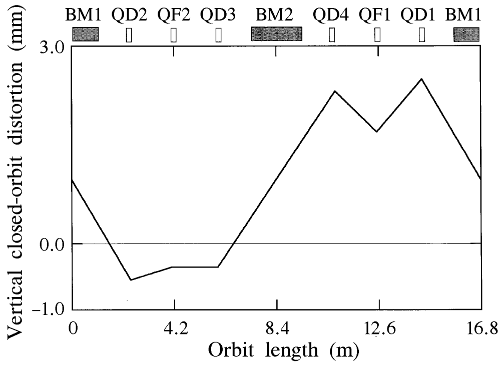


Figure 3
Closed orbit as an origin of skew-quadrupole perturbation.

The estimated skew-quadrupole perturbation originating from this closed orbit in the sextupole field of BMs is shown by the solid line in Fig. 4. In this estimation the coordinate systems are normalized by a Courant–Snyder transformation (Courant & Snyder, 1958). The phase parameter, φ, represents the position on the orbit, and it has a 2π advance for one turn of the ring. In Fig. 4 the phase $\varphi = 0$ coincides with the centre of BM1.

The coupling effect is mainly caused by the $k = 1$ component of the skew-quadrupole perturbation because the wave number is close to the tune difference of Super-ALIS. Therefore, only the perturbation of the $k = 1$ component is extracted from the original skew-quadrupole perturbation and is shown in Fig. 4 by the chained line. The $k = 1$ component has its peak at approximately $\varphi = \pi/2$, which is represented by the * symbol and corresponds to the position near QF2 in the real machine. The coupling reduction is performed by adding one skew-quadrupole magnet with a strength of $k_{\rm skmag} = -\pi f_1 = -7.6 \times 10^{-4}$ at this position.

3.3. *Tracking simulations*

For the tracking simulations we assumed the same closed orbit and the sextupole fields of BMs as those mentioned in the previous section. The observation points correspond to BL2 and BL9 synchrotron radiation ports.

The beam profiles are obtained by plotting the positions of the particles on the *X-Y* plane for all turns from 400 to 800. The validity of the simulation was confirmed by testing various initial distributions which have the same emittance value. The initial emittances are 4×10^{-6} m rad in the horizontal direction and 1×10^{-8} m rad in the vertical direction. This test showed that the obtained beam profiles are not very sensitive to the initial particle distributions; therefore, the simulation will give the equilibrium profiles.

Fig. 5 shows only the observed BL9 beam profiles. Without any cure for coupling, the tracking simulations resulted in tilted beam profiles in both BMs, as shown in Fig. 5(*a*). The flat beam profile in Fig. 5(*b*) is the result at BL9 when a skew-quadrupole magnet for coupling reduction is used. The profile at BM2 is also flat. These simulation results show that just one skew-quadrupole magnet will effectively reduce the coupling effect in both BMs.

3.4. *Experimental results*

We observed beam profiles at BL2 and BL9 with respect to the same closed orbit mentioned in the previous sections. Fig. 6

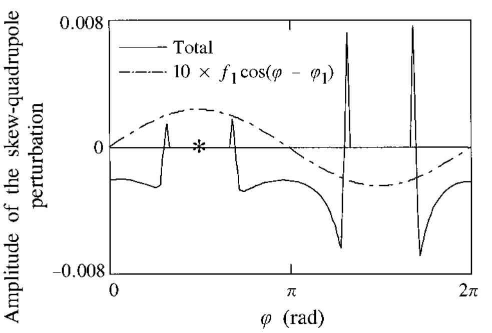


Figure 4
Skew-quadrupole perturbations originating from the closed orbit in the sextupole field of the BMs.

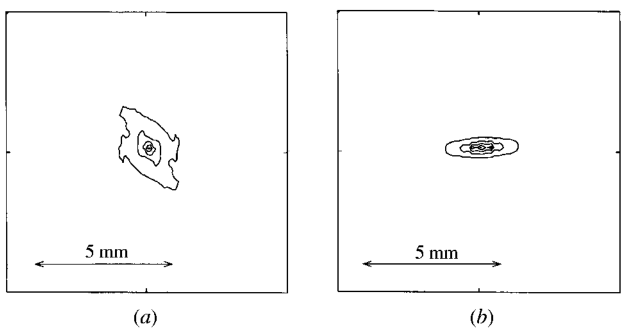
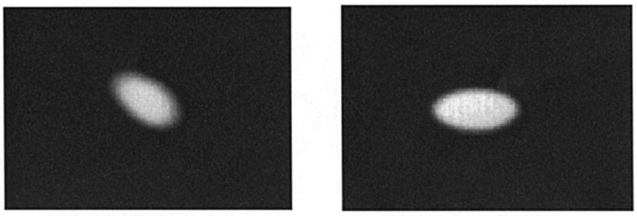


Figure 5
Tracking results of beam profiles at BL9 (*a*) before coupling reduction and (*b*) using a skew-quadrupole magnet near QF2.

shows only the observed BL9 beam profiles. The results qualitatively agree with the simulation results. The beam profile without any cure is significantly tilted. By using a skew-quadrupole magnet near QF2 we were able to make the beam profiles flat, as shown in Fig. 6(*b*). At BL2 the profile is also flat. The strength of the additional skew-quadrupole magnet was $k_{\rm skmag} = -2.4 \times 10^{-3}$, which was about three times larger than expected. This disagreement may be due to the rough approximation performed in deriving the method.



(*a*) (*b*)

Figure 6
Experimental results of beam profiles at BL9 (*a*) before coupling reduction and (*b*) using a skew-quadrupole magnet near QF2.

4. Conclusions

We have presented a coupling reduction method in which we only have to suppress the most harmful Fourier component of the skew-quadrupole perturbation. This method uses just one or two thin skew-quadrupole magnets; therefore, it should be a simple and effective method for coupling control in compact storage rings that have little space for correction instruments. The validity of this method was confirmed by simulations and experiments with the Super-ALIS machine. We effectively eliminated the tilts of the beam profiles originating from the vertical closed orbit in the sextupole field of the bending magnets.

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