STABILITY OF THE BETATRON OSCILLATION DURING THE OPERATION OF THE SUPERCONDUCTING WIGGLER IN THE PHOTON FACTORY

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ABSTRACT

The Photon Factory Storage Ring of KEK has been operated in cooperation with the superconducting vertical wiggler in the normal user's time. In the operation for one year, we have experienced a lot of operational problems, when the wiggler is in action in the storage ring. Results of the study on the stability of beams in the operation of the wiggler will be described.

INTRODUCTION

A wiggler magnet is one of the insertion devices which have been widely used in dedicated synchrotron radiation sources. Especially, the wiggler magnet applying superconductivity is capable of extending usable wavelength range to much shorter wavelengths. In the Photon Factory Storage Ring with the operating energy of 2.5 GeV, the characteristic wavelength is 3 Å for normal bending magnets, so that the intensity of radiation becomes very low at a wavelength less than 0.5 Å. Importance of intense hard X-rays from synchrotron radiation sources has been recognized for a long time, and a superconducting wiggler magnet has been intended to be installed in the Photon Factory from the beginning of the project[1].

Designs and operational experiences of the wiggler magnet will be described elsewhere in these Proceedings[2]. One special feature to be noted here for the wiggler magnet of the Photon Factory is that the magnetic field is in the horizontal direction; that is, it is the vertical wiggler in which the electron orbit wiggles in the vertical plane. Therefore, radiation from the vertical wiggler is polarized in the vertical plane, while the radiation is horizontally polarized in usual horizontal wigglers. The vertical wiggler is beneficial for designing high precision X-ray spectrometers, and for the study of crystal growth. This implies, however, a somewhat difficult technical problem in designing the wiggler magnet. Generally speaking, the magnet gap should be as small as possible, so as to obtain high field strength. Since the beam size is quite small after a radiation damping time, the beam-stay-clear of 30 mm should be sufficient. In the injection time, however, excursion of injected beams are much larger than the beam size, and the aperture of 100 mm is required. In order to fulfill both requirements, the vertical wiggler is provided with a T-shaped vacuum duct, as seen in Fig. 1. Injected beams pass through the wider part of the chamber, and the magnet is shifted down after the injection is finished. For this purpose, bellows of rather large size (265 mmϕ in reality) are needed on both ends. Since the space for bellows is limited in a given straight section, the stroke of vertical shift should be short. This requires that the superconducting coils should be as small as possible in the vertical direction, as can be seen in Fig. 1. It is clear that this requirement is contradictory to the magnetic requirement which claims that wider coil width is desirable for magnetic uniformity. Therefore, the final design was a compromise between two requirements.

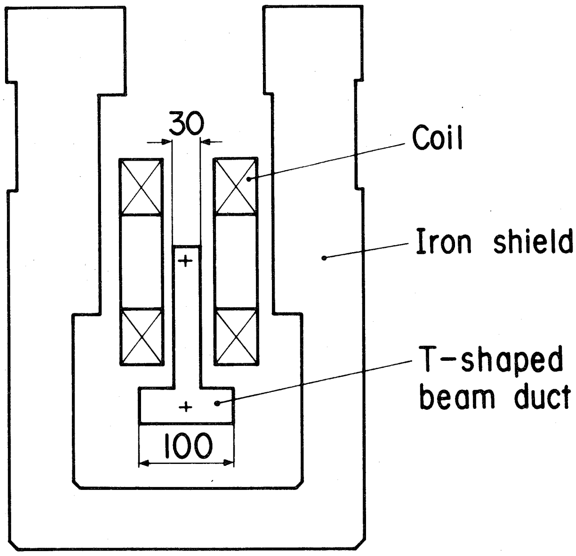

Fig. 1 Cross section of the central coil part of the vertical wiggler.

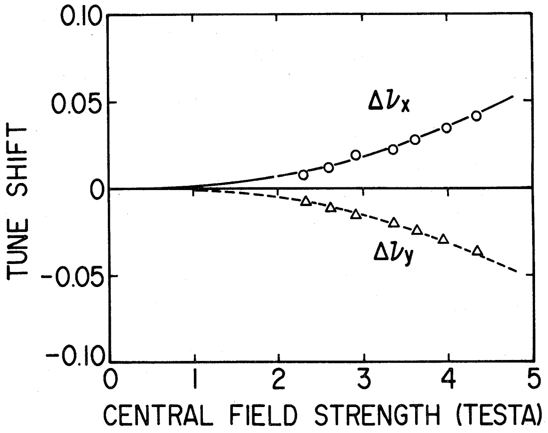

Fig. 2 Shifts of the betatron frequencies by the excitation of the wiggler.

This situation has given rise to a special operational problems in an actual operation of the storage ring. Especially, the regulation of the betatron frequencies must be stringent to obtain good beam quality. In this paper will be described the results of the study on the operating condition of the vertical wiggler, including the measurement of tune shifts, the resonance mapping, and the correction of tune shifts.

TUNE SHIFTS AND THEIR CORRECTION

The wiggler magnet consists of three superconducting coils. The central coil of nominally 6 Tesla is a parallel edge coil of 174 mm in length. Two outer coils are parallel edge coils of 137 cm in length, and their nominal field strength is chosen to be 3 Tesla in order to reduce radiation loss as far as possible.

If the magnetic field in the wiggler magnet could be approximated by a set of rectangular magnets with uniform field strength, the betatron frequency would change only in the horizontal plane, when the wiggler magnet is in operation. In fact, however, the betatron frequency changes in the vertical plane as well as in the horizontal plane, as seen in Fig. 2. This may be due to the non-linearity in the magnetic field of the wiggler, as discussed later. As described before, the wiggler magnet is ramped up after the injection is finished. Therefore, the betatron frequencies must be kept constant in the course of excitation of the wiggler, because there are many dangerous resonances in the vicinity of the operating point. In the actual operation, currents of ring quadrupole magnets, QF and QD, which are located in the normal cells, are changed in accordance with the prescribed relations between correction currents and the excitation of the wiggler. Figure 3 shows the variations of the horizontal and vertical betatron frequencies after corrections are performed. Although corrections seem to be incomplete, a certain amount of tune variation at the low level of excitation gives rise to no problem, as will be described later, and the correction of tune shifts as shown in Fig. 3 is completely satisfactory in the actual operation.

RESONANCE MAPPING EXPERIMENTS

From experiences of running the storage ring with the wiggler magnet, we have observed that the lifetime of stored beams at the usual operating field of 4.5 Tesla is very critical to the betatron tunes. Also we have sometimes experienced undesirable beam loss during excitation. These phenomena could be understood by resonance mapping experiments, in which we have recognized that unstable lines or regions exist in the vicinity of the usual operating point. Figures 4(a) to 4(c) show the results on mapping of resonance lines at three levels of wiggler excitation of 40 A (2.3 Tesla), 60 A (3 Tesla) and 106 A (4.5 Tesla). In these figures, solid lines represent resonance lines observed when the wiggler magnet does not work. The third order resonances $3\nu_x = 16$ and $2\nu_x + \nu_y = 15$ are so strong that the stored beam is lost abruptly on these lines. The resonances indicated by A, B, C and D are weaker than the previous lines, but the lifetime of stored beams is shorter on these lines than in the area surrounded by them. Lines (A) and (B) could be identified clearly to be synchrobetatron resonances of the third order; (A) $3\nu_x - 2\nu_s = 16$ and (B) $2\nu_x + \nu_y + \nu_s = 15$. But the identification of resonance lines (C) and (D) is rather difficult, but it seems that the line (D) is $\nu_x + 3\nu_y + 5\nu_s = 18$.

When the excitation of the wiggler magnet is 2.3 Tesla, two new resonance lines appear, on which the beam lifetime becomes shorter, as seen in Fig. 4(a) by dashed lines. One of the lines seems to be the third satellite of $3\nu_x = 16$, while identification of another line is difficult. As seen in Fig. 4(b), there appears one more line at 3 Tesla, which corresponds to the second satellite of $2\nu_x + \nu_y = 15$. Also, the widths of stronger resonances become wider than at the low level of excitation. As the wiggler excitation level increases, this trend is accelerated. At 4.5 Tesla, the stable operating area become narrower than before, since new resonance lines appear and old lines become broader. Results shown in Fig. 4(c) indicate that the betatron tune must be maintained within 0.005, in the vicinity of the normal operating point, at least in the high excitation levels.

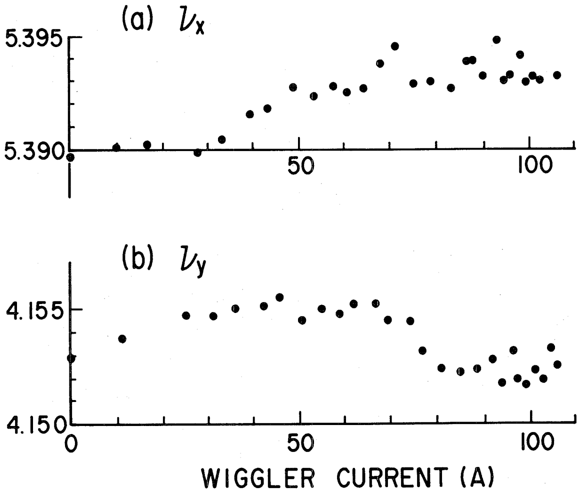

Fig. 3 Corrected betatron frequencies as functions of the exciting current of the wiggler.

An effort to fined out much wider operating area has been continued. Figure 5 shows another example obtained at 4.5 Tesla. In this case, unstable points are distributed in a complex way, so that it was very difficult to draw distinct resonance lines from the results of lifetime mapping experiments, except for three lines indicated by solid and dashed lines in the figure. Resonances on the solid lines are strong, so that decay of stored beams is steep on these lines. It is clear that the resonance A is the first satellite of $3\nu_x = 16$, but identification of lines B and C is difficult. The resonance line C is weaker than A and B. A triangular shaped area is rather wide, compared to the former case. Therefore, it should be easy to operate the wiggler magnet in this region of tunes. But, this is in the unstable region with respect to the transverse coupled bunch instability[3] so that we can not store stable beams of more than 10 mA at these operating tunes, at this moment.

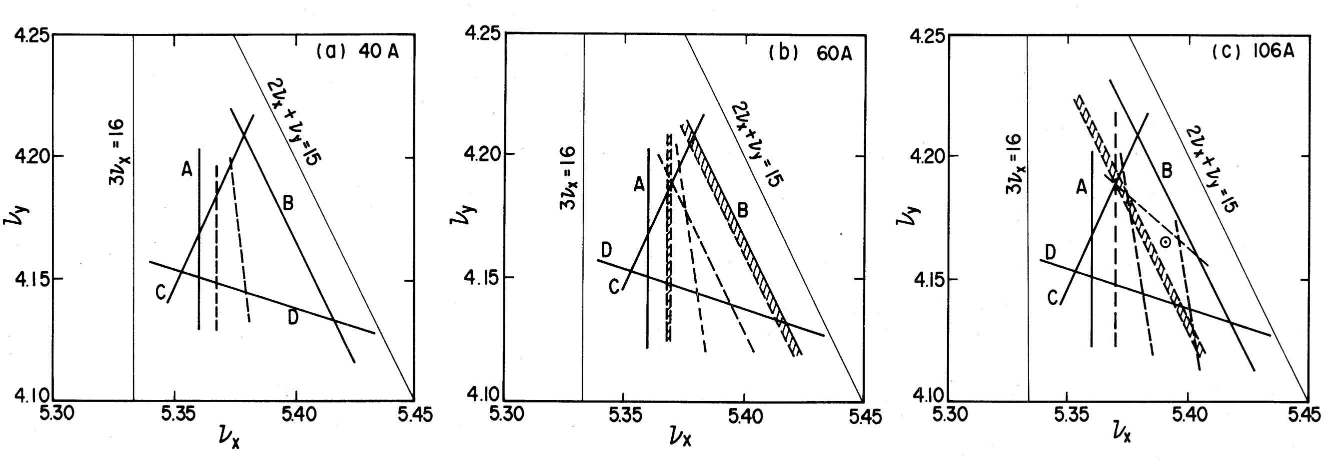

Fig. 4 Results of resonance mapping. (a) the wiggler excitation 40 A (2.3 Tesla), (b) 60 A (3 Tesla) and (c) 106 A (4.5 Tesla). In (c) the mark indicates the normal operating point in the recent operation of the Storage Ring.

DISCUSSIONS

As remarked before, the betatron tune in the vertical plane should not change, if the vertical wiggler could be approximated by a set of rectangular magnets with uniform field distribution. In the actual magnet, however, the magnetic field distribution is not uniform in the lateral direction.

The magnetic measurement, especially the measurement of the transverse distribution, is difficult in practice, because the physical aperture of the wiggler beam duct is only 30 mm. In addition, for the purpose of magnetic measurement, extra chamber of 20 mm in inner diameter must be put in the cold bore of the wiggler for thermal insulation, so that available aperture becomes very small. Therefore, we only measured the distribution along the magnetic centerline, and we refer to the results of calculation using the computer for the transverse distribution. According to the calculation, the transverse distribution can be fairly well approximated by a sum of dipole and sextupole fields. Results of the distributions of dipole and sextupole fields along the beam direction are shown in Fig. 6.

In the following, we will roughly estimate the betatron frequency shift due to the wiggler by using the calculated values of the magnetic field of the wiggler. For the betatron oscillation in the plane parallel to the direction of the magnetic field, i.e. in the horizontal plane in this case, the tune shift can be considered to be originated by the non-normal entrance and exit to the magnet edge, and not to be affected by the non-linear fields in the first approximation. The tune shift due to edge focusing can be calculated easily and is turned out to be 0.04 at the excitation of 4.5 Tesla. Since the measured value is 0.05, agreement is quite good.

For the tune shift in the vertical plane, which should be zero in ideal parallel-edged magnets, can be considered to be due to non-linear fields. Considering the orbit deviation is ±5 mm from the magnet centerline of the wiggler, the estimated value of the tune shift is 0.028 at 4.5 Tesla, which is in good agreement with the measured value of 0.04. Contributions from the central coil and the outer coils are additive, so that the position of the beam relative to the magnet centerline of the wiggler does not affect the tune shift in the first approximation. Instead, an amount of the orbit wiggle is primarily important to give the tune shift.

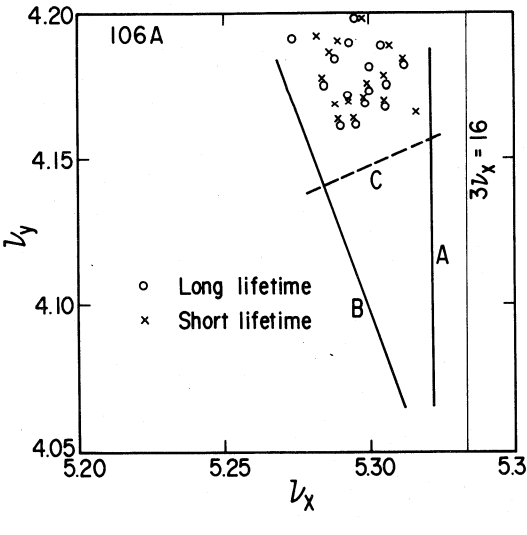

Fig. 5 Result of resonance mapping at another frequency region. The wiggler excitation is 106 A (4.5 Tesla).

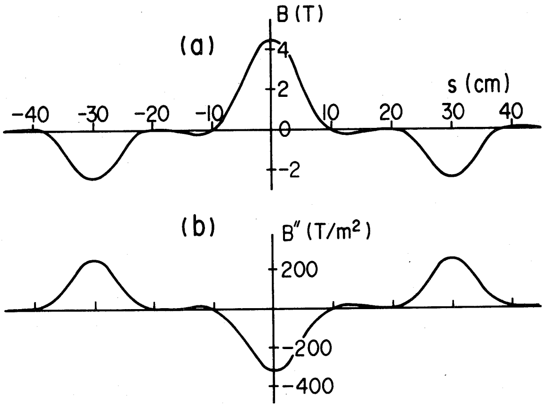

Fig. 6 Calculated field distribution in the wiggler. (a) dipole field, (b) sextupole field. s means the beam direction.

The lifetime of stored beams is about 6 hours at 150 mA and more than 20 hours at 60 mA. The reasons for the lifetime deterioration at the high stored current may be (a) increase in vacuum pressure, (b) increase in beam size, and (c) growth of the amplitude of the synchrotron oscillation. Although the vacuum pressure is an important factor to determine the beam lifetime, it is unlikely to explain the deterioration of the lifetime in this case solely by pressure increase. Since the physical aperture of the wiggler beam duct is small, an increase in the beam size may be dangerous to the beam lifetime. In the Photon Factory Storage Ring, the longitudinal coupled bunch oscillation exists above the current of about 40 mA. The coupled bunch oscillation is due to a higher order mode resonance of the cavity[4]. The threshold current and the growth rate of the oscillation amplitude is dependent on the operating condition of the cavity; e.g. the temperature of each cavity. The horizontal beam size at 150 mA blows up by 20 % under the properly adjusted situation, but by more than 70 % when the adjustment is not complete. As a result, the beam lifetime becomes shorter; for example 200 minutes. In addition, considering that the number of synchrobetatron sidebands appear in the vicinity of the operating point, the amplitude growth of the synchrotron oscillation may be one of the causes to reduce the beam lifetime at high currents. Therefore, the beam loading power and the cooling water temperature among four cavities have been adjusted carefully to suppress the longitudinal coupled bunch instability[5].

Although we have operated the wiggler magnet at 4.5 Tesla in the usual operation, we have tried the operation above that field for many times. By this moment, however, we have not achieved the beam lifetime long enough for the user's run. It seems that nonlinearlity in the magnetic field of the wiggler is the main cause of short lifetime. In addition, as the magnetic field strength increases, the vacuum pressure in the vicinity of the wiggler becomes worse due to heating of the vacuum chamber by harder X-rays.

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