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BEAM LIFETIME IN THE INITIAL OPERATION OF KEK MAIN RING

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Summary

In the initial operation of the main ring of KEK PS, efforts have been put on improving the beam life by incorporating the correction lenses as well as reducing the emittance of the booster beam and the injection error. The transmission of 30 % at 0.5 sec after injection was obtained at the time of writing. This paper describes the performance of the main ring with respect to the beam life and discusses the problems to be solved.

Introduction

The main ring of KEK PS is filled with nine bunches of the 500 MeV protons from the booster which is operating at the repetition rate of 20 Hz. The transport and injection system from the booster to the main ring will be described elsewhere in these Proceedings[1] Since the elapsed time for the injection is 0.5 second, the beam life has to be sufficiently longer than the injection time. The beam life depends on the qualities of the beam such as the amplitude of the betatron oscillation and the momentum spread, and the aperture of the ring. The aperture mentioned here is not only the physical obstruction but also the magnetic aperture. Since there are various resonance lines near the operating betatron tune, some of the particles may cross those lines, then the resultant emittance blow-up leads to the beam loss. The growth rate of the beam size depends on the strength of non-linear fields of the lattice quadrupole and dipole magnets.

In order to correct the magnetic imperfection and eliminate the effects of various nearby resonance lines, we have used the correcting sextupoles, skew quadrupoles and octupoles. Up to the present time, the average of these multipole fields has been corrected, and it has been found that the correction is effective for improving the beam life. Since the relevant choice of the betatron tune is also important, we have surveyed the tune diagram to find the operating point of good beam life. The qualities of incoming beam are also important; i.e. the emittance growth due to the coherent injection error and the mismatch of emittance ellipse is harmful, because the bandwidth of non-linear resonance depends on the emittance. Therefore, efforts have been put on reducing them as small as possible.

Closed Orbit Correction

The first we did is the closed orbit correction. The closed orbit is corrected by the steering dipoles placed next to the focusing and defocusing quadrupoles. The local orbit bump is produced by three correction dipoles with appropriate current ratio. The orbit is measured by the fast position digitizer[2] and is visualized on the graphic display. The distortion was corrected within ±5 mm and ±2 mm in horizontal and vertical planes, respectively.

The local orbit bump was used in order to see a margin of aperture. Changing the amount of local bump, the intensity of second turn was compared with that of the first turn. The aperture survey showed that the margin of ±25 mm is reserved in the horizontal plane. In the vertical plane, the marin is more or less ±10 mm. We also made the aperture survey by comparing the intensity at 100 μs after injection with the intensity of first turn. In this case the margin of horizontal aperture was ±25 mm, just the same as the previous one. In the vertical plane, however, there remains little margin or at the best ±5 mm. This is a crucial problem to be solved at the time of writing, since this may limit the beam life. The fact that the beam is lost in the vicinity of defocusing quadrupoles according to the loss monitors and the residual activity in the ring is really strong there agrees with the aperture survey.

The vertical emittance of the injected beam and the corresponding beam width are 17 π mm mrad and 37 mm, respectively. Even if we assume the closed orbit distortion of ±2 mm and the injection error of 0.1 mrad (producing the coherent oscillation of ±2 mm), the overall beam width becomes 45 mm, which should be compared with the vertical aperture of 50 mm. On the other hand, the horizontal width of the beam in the ring is 80 mm, including the injection error. The reason for the beam loss near the defocusing quadrupoles may be the third or higher order resonances in the vertical plane, or the horizontal-vertical coupling resonances. As discussed later, the horizontal-vertical coupling seems to play a major role on the beam loss.

Chromaticity correction

The tune spread should be reduced as small as possible, since there are various resonance lines near the operating betatron tune, and crossing these lines leads to the beam loss. The tune spread $\Delta\nu$ arises from the momentum spread $\Delta p/p$ of the circulating beams. The value of ν for different momenta was measured by biasing the rf Δr feedback loop and observing the coherent motion produced by the pinger dipole. Uncorrected chromaticity is given by $\Delta\nu_x = -18.6\ (\Delta p/p)$ and $\Delta\nu_z =$

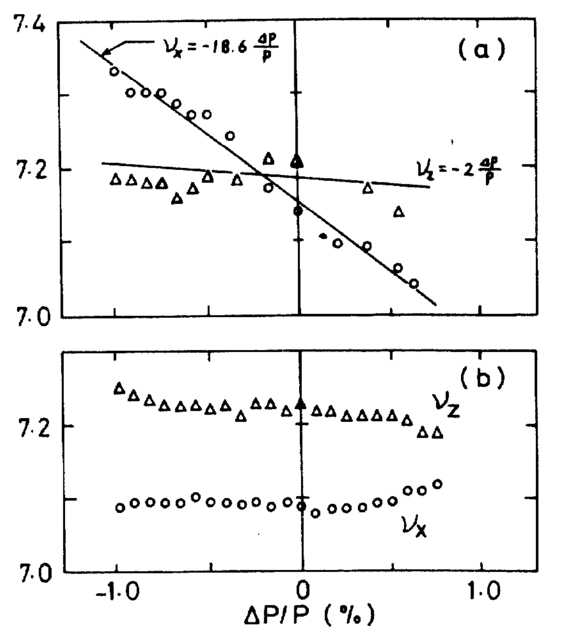

Fig.1 Chromaticity of the main ring. (a) uncorrected, and (b) corrected with F-sextupole of 2.0 A and D-sextupole of zero current.

-2.4 ($\Delta p/p$) as shown in Fig.1(a). Note that the relation between $\Delta\nu_z$ and $\Delta p/p$ is the calculated one, using the sextupole term of the bending magnet $B''/B = -1.33\ m^{-2}$ estimated from the least-squares fit of $\Delta\nu_x - \Delta p/p$ relation. The chromaticity due to the momentum dependence of the focusing strength of the lattice quadrupoles is $\Delta\nu/(\Delta p/p) = -9.5$.

The momentum spread of the injected beam can be measured by the method which is based on the debunching time of bunch shape without rf voltage.[3] The measured value of momentum spread was less than $\pm 3 \times 10^{-3}$. The tune spread corresponding to this value becomes $\Delta\nu_x = \pm 0.05$ and $\Delta\nu_z = \pm 0.02$ without the chromaticity correction. These are untolerable, since the resonance lines closely exist in the vicinity of the operating tune. Actually, the beam lifetime becomes shorter without correction.

The chromaticity was corrected by 16 sextupole magnets, half of them being placed next to the focusing quadrupoles, and another half next to the defocusing quadrupoles. These are excited by independent power supplies, so that they can also provide with the harmonic correction of third order non-linear resonances. As shown in Fig. 2, the intensity map is the (I_F, I_D) diagram suggests the optimum current of correcting sextupoles. As an example, the corrected chormaticity when $I_F = 2.0$ A and $I_D = 0$ is shown in Fig.1(b). The non-linearity of the ν vs $\Delta p/p$ relation is small in

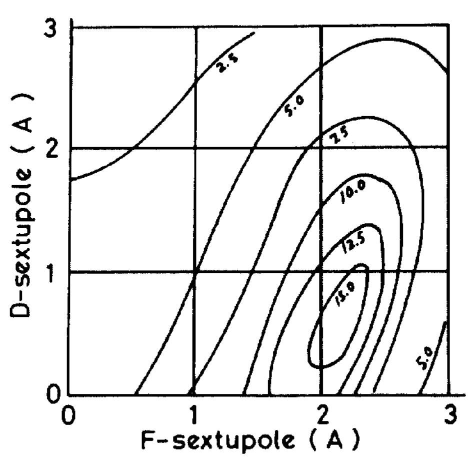

Fig.2 Intensity map in the diagram of F-sextupole and D-sextupole current.

the practical point of view, but it may come from the higher order non-linear fields and should be corrected.

It should be mentioned that the damping of coherent oscillation signal detected by the pick-up electrode is correlated to the tune spread. Before correction, the coherent oscillation in the vertical plane lasts for more than a hundred turns, while in the horizontal plane the oscillation damps much faster. After correction, the oscillation lasts to more or less 30 turns. This gives approximately the tune spread of 0.03. This may be related to the amplitude dependence of tune, as described later.

Skew quadrupole correction

Skew quadrupoles were effective to improve the beam life. At the present time, the 16 skew quadrupoles are connected in series and powered by one power supply. We have studied the effect of the $\nu_x = \nu_z$ coupling resonance on the beam life. For measuring

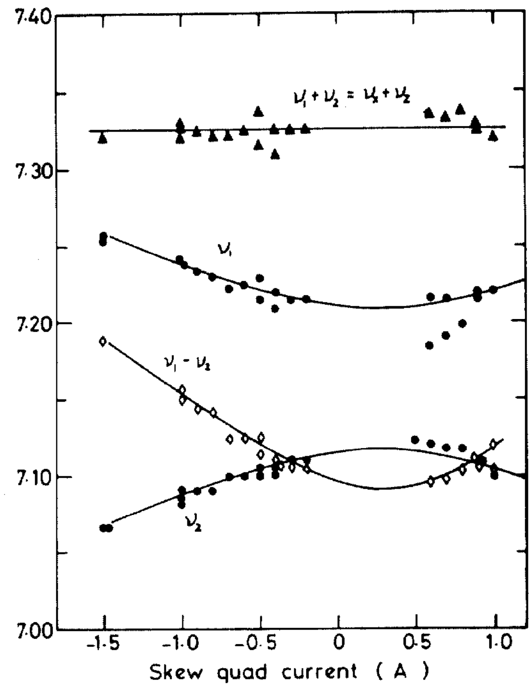

Fig.3 Two frequency components appearing in the vertical coherent oscillation signal when kicked horizontally.

the strength of the skew quadrupole field to be corrected, the current of the correction skew quadrupoles was varied and the shift of betatron frequency was measured. When the beam is kicked in the horizontal plane, the betatron oscillation in the vertical plane can be expressed in the following form;

$$Z = Z_c\sqrt{\beta_z}\cos\omega\theta\cos[(\nu_z+\tfrac{\Delta}{2})\theta + \phi_z],$$

where $\omega = \sqrt{(\frac{\Delta}{2})^2 + \kappa^2}$, κ is the coupling coefficient given by $\kappa = \frac{1}{4\pi B\rho}\int_0^{2\pi R}\sqrt{\beta_x\beta_z}\,B'_{SQ}\,ds$ and $\Delta = \nu_x - \nu_z$. Z_c is the amplitude of the coupled oscillation and is given by $Z_c/x_c = \frac{\kappa}{\sqrt{(\frac{\Delta}{2})^2 + \kappa^2}}$. The signal of coupled oscillation observed by a vertical pick-up electrode was analysed in the Fourier transformation by the automatic Q-meter.[4] The two frequency components are observed with equal amplitude; $\nu_1 = \nu_z + \frac{\Delta}{2} + \omega$, $\nu_2 = \nu_z + \frac{\Delta}{2} - \omega$. Fig.3 shows the results of measurement. We can get the optimum strength of the correcting skew quadrupole from the point where the separation of two frequencies becomes minimal. Actually, the beam life became the best for this value of skew quadrupoles. At that point we can also obtain uncoupled betatron frequencies ν_x and ν_z, i.e. $\nu_x = 7.12$ and $\nu_z = 7.21$ in this case. Using the value of skew quadrupole field strength, the error field term can be estimated. This is equivalent to the quadrupole magnet tilt of 1 mrad on the average.

Octupole correction

From the fact that the damping of coherent oscillation was fast even if the chromaticity correction was performed, as described before, it seems that the amplitude dependent tune spread exists. Then, we measured the damping time of coherent oscillation produced by the pinger dipole by changing the octupole field

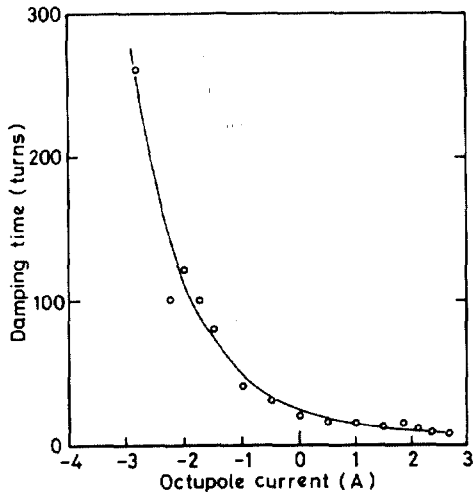

Fig.4 Damping of coherent oscillation with current of correcting octupole magnet.

strength. As the number of turns for the coherent oscillation to damp to 1/e is related to the tune spread roughly by $n = 1/\Delta\nu$, the damping time should change hyperbolically with the current of correcting octupole magnet. Fig.4 shows the agreement with this statement. We used two groups of octupole magnets; 12 octupoles next to the focusing quadrupole magents and 12 octupoles next to the defocusing quadrupole magnets. These are connected to the independent power supplies, so that the tune spread in both planes can be corrected.

The existance of amplitude dependent tune spread was also suggested by the following thing; the coherent oscillation signal damps more slowly when the width of circulating beam is narrowed with the scraper.

The effect of the octupole magnets on the beam life has been studied preliminary. At the off-diagonal operating tune (7.1, 6.2), the effect of octupole magnets was not observed, but more careful investigations will be needed.

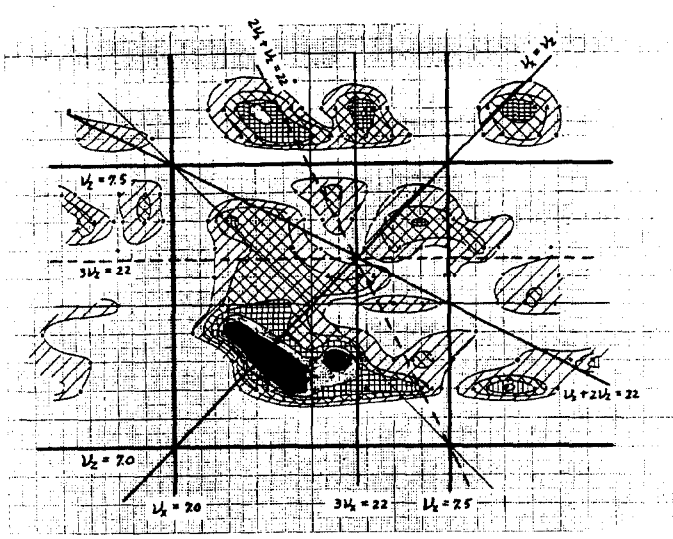

Fig.5 Intensity map in (ν_x, ν_z) diagram.

Choice of operating point

The nominal operating point of the main ring is $\nu_x = \nu_z = 7.25$. Since the beam life depends strongly on the betatron tune, what we did is to change the current of focusing and defocusing quadrupoles and investigate the transmission of beams to 0.2 sec after injection. According to the intensity distribution in the (ν_x, ν_z) map shown in Fig.4, we have found the best operating point exists around 7.15. The normal operating tune is (7.10, 7.20).

We have also searched the possibility of operating the main ring in other tune values, such as (7.15, 6.15), (6.15, 7.15) and (6.15, 6.15). The first two of them have an advantage that they are free from the $\nu_x = \nu_z$ coupling resonance. The operation at these tune values was possible and particularly the first of them can offer the comparable or better transmission compared with the normal operating point. As for the initial beam loss to 100 μs after injection, loss is smaller for the off-diagonal operating point (7.10, 6,20) than the normal (7.10, 7.20). This may suggest that the fast beam loss occurs due to the coupling resonances.

As a possible source of beam loss, the fourth-order coupling resonance $2\nu_x - 2\nu_z = 0$ driven by the N = 6 order nonlinearity in the quadrupole magnet and the closed orbit distortion due to momentum error has been suggested by T. Suzuki.[5] Near the $2\nu_x - 2\nu_z = 2$ octupole resonance, the systematic structural stopband disappears, since the main ring has the superperiodicity of four. The good transmission at the off-diagonal tune may reflect this possibility.

The narrow beam has a better transmission than the wide beam. If the beam is scraped horizontally by the use of the three dipole local orbit bump, the resultant narrow beam has a good transmission. On the contrary, when the beam is scraped vertically, the beam lifetime is almost the same as the wide beam. This may also suggest that the vertical emittance blow-up due to coupling is one of the sources of beam loss.

On the average, 30 % of the injected beam survives during the injection porch of 0.5 sec. For the booster intensity of 2.5×10^{11} protons per pulse, 1.0×10^{11} ppp was obtained at the maximum energy. When nine bunches were injected from the booster, the maximum intensity was 5.4×10^{11} ppp at the time of writing.

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