# Beam Dynamics

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## Introduction

In SPring-8 the beam dynamics group has been in charge of lattice design and beam stability analysis. Improvement of the lattice and refinement of stability analysis are now going on in addition to design work of graphical interface of a control system. In the following, we pick up some topics of interest and give an outline. Further details can be found in refs.[1]-[9].

## Coupling of betatron oscillations and skew compensation

Since the brilliance of X-ray beams from various SR sources is inversely proportional to the product of horizontal and vertical emittances of the electron beam, one can obtain high-brilliance X-ray beams by reducing the vertical emittance. This can be done by controlling the horizontal-vertical (H-V) coupling ratio of betatron oscillations.

In low-emittance electron storage rings, like SPring-8, a major part of the vertical emittance comes from H-V coupling of betatron oscillations. This coupling is induced by skew-quadrupole components of error fields associated with quadrupole and sextupole misalignment. In ref.[1] the authors derived analytical formulas for describing modulation of horizontal and vertical betatron oscillations by assuming that a single linear coupling resonance is excited. The most important result is that the area of phase space, or the emittance (especially the vertical emittance) in the laboratory frame is not constant and varies point by point along the circumference of the ring. The formulas are generally applicable to the rings with any nonlinear fields. They applied the formulas to the SPring-8 storage ring and calculated vertical emittance modulation along the ring.

Based on these formulas, they also proposed two kinds of correction scheme for the H-V coupling. It was found that the formulas are useful for both global and local correction of the coupling.

## Reduction of natural emittance

As explained above, the brilliance of X-ray beams can be increased by reducing the vertical emittance of the stored electron beam. Another way of increasing brilliance is to reduce the natural emittance of the beam.

In general, the Chasman-Green lattice includes dispersion-free straight sections for insertion devices. In order to reduce the emittance under the constraint of dispersion-free (achromatic) condition, one needs strong quadrupole magnets. For correcting chromaticity, one then needs strong sextupole magnets, and the strong sextupole fields give rise to a small dynamic aperture. The minimum emittance is thus limited in the achromatic lattice.

In ref.[2] it was pointed out that one can obtain a large enough dynamic aperture even when the achromatic condition is broken to reduce the natural emittance and thus to increase the brilliance. The minimum emittance under the non-achromatic condition was found to be three times smaller than that under the achromatic condition. Efficiency of this scheme in the SPring-8 storage ring is under investigation.

## Transverse instability

In discussing stability of a stored electron beam it is essential to estimate broadband impedance of the vacuum chamber of the ring. The impedance can be estimated by using the two-dimensional (three-dimensional) simulation code MAFIA T2 (MAFIA T3). In ref.[3] the author evaluated longitudinal impedance $Z_{\|}$ and transverse impedance $Z_{\perp}$ for the SPring-8 storage ring. The analysis includes the effects of a detailed three-dimensional structure of the chamber, e.g. a structure of slots to ante-chamber, and the difference between a round chamber and an elliptical chamber. The following relation was then tested: $Z_{\perp 1}(\omega) \cong (2c/b^2\omega)\, Z_{\| 0}(\omega)$, where the constant $b$ represents a typical size, such as radius, of the vacuum chamber and has dimension of length. From this one can derive $W'_1(z) \cong (2/b^2)\, W'_0(z)$ by using the Panofsky-Wenzel theorem. These useful relations were found to be valid even in the three-dimensional treatment if one uses a suitable value of $b$. Details of the calculations are shown in ref.[3] together with numerical results.

Based on these studies, we are now improving calculations on beam instability, aiming at higher performance of the ring.

## Equilibrium bunch length with RF noises

In proton storage rings it is important to solve problems caused by noises in RF system in order to keep long term stability against diffusion. This is because phase feedback between beam and RF is essential. In electron storage rings such problems can be neglected in view of stability because the stochastic process of quantum radiation smears out any history of motion. However, in order to obtain an equilibrium longitudinal emittance (or density distribution), RF noises must be included in the same way as quantum excitation. In ref.[4] the authors derived formulas which give the equilibrium r.m.s. value of a longitudinal density distribution when RF phase noises are significant in an electron storage ring. These noises are caused by a ripple of the acceleration voltage in klystrons. An interesting result is that the effect of a systematic noise (deviation), which is a source of forced oscillation, is not symmetric in energy and phase. Numerical estimates are also given in the reference for the SPring-8 storage ring.

## Slow positron production

An intense positron beam with very low energies is a useful tool in solid state physics, materials science, etc. If we can install a superconducting (S/C) wiggler with field strength of 8-12T in the SPring-8 storage ring, such an intense positron beam ($10^8$ - $10^{10}$ slow-$e^+$/s/mrad/100mA) will become available since high-energy gamma rays create positrons in a target slab through electron-positron pair production process [5].

In ref.[6] the authors have checked the effect of a S/C wiggler on tune, amplitude function, dynamic aperture, and emittance by using a simple model. It was found that it is necessary to keep residual dispersion in the vertical plane as small as possible in order to maintain a given horizontal-vertical coupling ratio.

Another problem of importance is the heat load caused by the synchrotron radiation. A S/C wiggler with strength 8T, for example, generates the power of ~60kW for 100 mA beam current, and the divergence angle of the radiation is about 18 mrad. They have checked that after suitable modifications of the vacuum chamber, crotch and absorbers, it is possible to absorb such radiations.

## Super-long straight section

A characteristic feature of SPring-8 is that after rearranging the lattice with minimal modifications, four super-long (~30m) straight sections can be realized in the storage ring [7]. These sections can accommodate, for example, a long undulator or a series of undulators, and with these undulators X-ray beams with higher brilliance or broader bandwidth will become available.

The super-long straight sections are realized step by step. In the first phase of commissioning, the ring is operated in highly symmetric lattice configuration without the super-long straight sections in order to reduce the sensitivity against error fields. In this operation mode the lattice is composed of 4 straight cells and 44 normal cells. The super-long straight sections are realized in the second phase: all magnets in the straight cells and some neighboring quadrupole and sextupole magnets are rearranged. The arrangement of lattice structure has been improved [8], and we are now planning to rearrange the lattice after the first phase of commissioning. The task force is to develop an algorithm to realign magnets in arc sections using the c.o.d. data in beam commissioning.

## Radiation spectra from a very long undulator

The brilliance of undulator radiation is expected to be proportional to the square of the number of undulator period. Then, if we install in the super-long straight section a very long, for example 30 m long, undulator instead of a normal undulator, we may have a 60 times higher brilliance. According to numerical calculations, however, it turns out that the brilliance is not so high as expected. This is because the brilliance is closely related to the emittance of the electron beam.

In ref.[9] the authors studied the spectral properties of the synchrotron radiation from a 30 m long undulator. They investigated the dependence of radiation intensity on the electron beam emittance and on the transverse emitttance coupling.

The spectral calculation was first made with the far field approximation as usually done. They further estimated the near field effect in the radiation intensity since the undulator is relatively long compared to the observing distance. Details can be found in ref.[9].

**References**

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