ESTIMATION OF VERTICAL EMITTANCE IN AN ELECTRON STORAGE RING WITH VERTICAL DISPERSION AS A PROBE

H. Tanaka, K. Kumagai, N. Kumagai, M. Masaki, H. Ohkuma, K. Soutome, M. Takao,
SPring-8/JASRI

Abstract

We present a new idea to estimate small vertical emittance of a few pm.rad-order in an electron storage ring. The emittance reduction is important for synchrotron radiation sources providing brilliant photon beam. And also, its estimation is crucial from the viewpoint of precise control. In our method, vertical dispersion is used to systematically change the vertical beam size along the ring. Vertical dispersion of 1 mm, which is sufficiently controllable by skew quadrupoles, corresponds to the vertical beam size of 1 micron. This becomes a good probe when the vertical beam size is the same order of 1 micron. The magnitude of vertical emittance is clearly reflected by the response of physical observables which depend on the emittance in changing the dispersion. Vertical emittance can be thus estimated by analyzing the dependence of Touschek lifetime on the change of vertical dispersion with 4×4 ring model describing the measured dispersion. By applying our method to the SPring-8 storage ring, vertical emittance values for “HHLV” and “Hybrid” optics are estimated to be respectively 5.5 and 5.1 pm.rad in the nominal operation condition.

1 ESTIMATION METHOD

Vertical emittance ε_y of high energy electron beam in a storage ring is described by two main contributions, radiation excitation ε_{y_r} and coupling between horizontal and vertical betatron oscillations ε_{y_c}. Assuming that longitudinal and transverse motions are independent with each other, rms. vertical beam size $\sigma_y(s)$ at an azimuthal position s has a bi-gaussian form of

$$\sigma_y(s) = \sqrt{\beta_y(s)\cdot\varepsilon_y + \eta_y^2(s)\cdot\sigma_\delta^2}\ , \qquad (1)$$

$$\varepsilon_y = \varepsilon_{y\_c} + \varepsilon_{y\_r}\ ,$$

where $\beta_y(s)$ and $\eta_y(s)$ are respectively vertical betatron and dispersion functions and σ_δ is rms. momentum spread.

By changing distribution of vertical dispersion conserving the resonance condition, we can systematically change the vertical beam size along the ring through the excitation parameter, p_{excite} defined in Eq. (2). An averaged vertical beam size is written by Eq. (3) and Touschek lifetime τ_t is inversely proportional to the averaged vertical size. By measuring the dependence of Touschek lifetime on the excitation parameter, we can estimate the vertical emittance with Eq. (3) as a sum of ε_{y_c} and ε_{y_r}.

$$p_{\mathrm{excite}} \equiv \beta_y\cdot\varepsilon_{y\_r} + \eta_y^2\cdot\sigma_\delta^2\ . \qquad (2)$$

$$<\sigma_y> = \sqrt{<\beta_y>\cdot\varepsilon_{y\_c} + <p_{\mathrm{excite}}>}\ \propto \frac{1}{\tau_t}\ , \qquad (3)$$

$$<p_{excite}> \equiv <\beta_y>\cdot\varepsilon_{y\_r} + <\eta_y^2>\cdot\sigma_\delta^2 \propto <\eta_y^2>\ ,$$

$$<\beta_y> \equiv \frac{1}{L_c}\cdot\int_{L_c} ds\ \beta_y,\ \ <\eta_y^2> \equiv \frac{1}{L_c}\cdot\int_{L_c} ds\ \eta_y^2\ .$$

A main estimation error comes from the variation of resonance condition during the measurement. As discussed in section 3 and 4, this error we estimate to at most 1 pm.rad. On the other hand, an advantage of this method is to keep the ring condition almost the same and then this improves the estimation accuracy compared with the previous method with widely changing an operation point of the ring [1].

2 OPTICS

Two kinds of optics were used in our experiments. One is of 48 mirror symmetry having high horizontal and low vertical betatron functions at all straight sections for insertion devices (IDs), which is called “HHLV optics” and being used in the present user operation. The other is of 24-fold symmetry alternatively changing a high and low horizontal betatron function at the straight sections, which is called “Hybrid optics” and had been used in the user operation until autumn 1999. In section 3, the Hybrid optics is used for the calculation and in section 4, the both are used depending on the purpose.

3 REQUIRED NUMBER OF SUPPRESSING RESONANCE LINES

For the precise measurement, it is crucial to conserve the resonance condition. The strengths of skew quadrupoles are changed to keep the linear coupling as constant as possible. We have thus investigated how many resonance lines near the operation point should be suppressed to prevent the coupling excitation.

To estimate the coupling excitation, we use a ratio of V emittance to V_1 emittance. Here, the V represents one eigen mode of a coupled betatron oscillation, which eventually corresponds to a vertical mode without any H-V coupling element. The V emittance therefore includes both the radiation excitation and the linear coupling contribution. The V_1 represents a pseudo-vertical mode and V_1 emittance is calculated by setting off-diagonal parts of 4×4 matrix to zero for the coupled betatron oscillation.

The V_1 emittance then only includes the radiation excitation contribution.

In Fig.1, we show the calculated dependence of the above emittance ratio *R* on the number of suppressing resonance lines N_R for three different distributions of vertical dispersion. In this figure, the emittance ratio is normalized by that of $N_R = 8$ for each case. We found that the emittance ratio converges to the unity in the region where N_R is larger than four. From this result, we have determined to suppress six sum and differential linear coupling resonance lines near the operation point in changing the strength of skew quadrupoles.

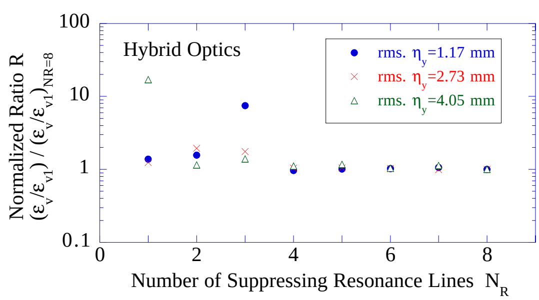

Figure 1: Effect of the number of suppressing resonance lines on the excitation of linear coupling

With the above resonance suppression criterion, we have widely changed the vertical dispersion from 1 to 5 mm in an rms. value and calculated the emittance. The results are shown in Fig.2. The U and U_1 represent respectively another eigen mode corresponding to the horizontal one and pseudo-horizontal mode. We found that U and V emittance values have good agreement respectively with those of U_1 and V_1 in this calculation range. Since the difference between V and V_1 values is the extra coupling contribution generated by changing the skew quadrupole strength, we see that it is much smaller than 1pm.rad. We also found that V emittance is scaled by a square of rms. vertical dispersion. This is because the amplitude of vertical dispersion is modified keeping its oscillation phase unchanged as shown in Fig.6.

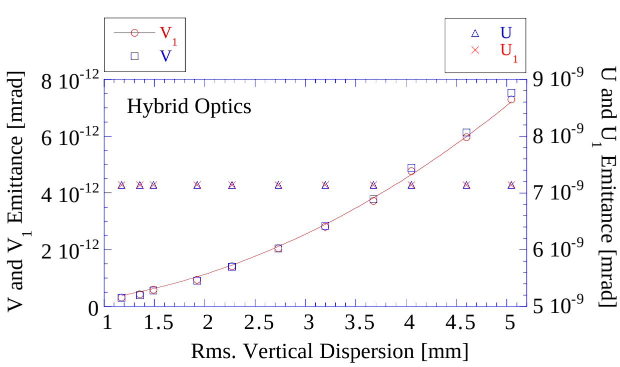

Figure 2: Eigen mode emittance as a function of rms. vertical dispersion (model calculation)

4 EFFECTS OF WEAK SKEW QUADRUPOLE PERTURBATION

To see that the ring condition is kept almost constant during the measurement, we have calculated dependence of optics characteristics on the change of skew quadrupole strength. We impose the criterion for the resonance suppression discussed in section 3 on solving the strength distribution of skew quadrupoles.

In Fig.3, we show the calculated amplitude-dependent tune shift for the hybrid optics using the skew quadrupole strength distribution and the relative momentum deviation as parameters. The momentum deviation of ± 1.3 % corresponds to the measured momentum acceptance. And at this acceptance, the maximum oscillation amplitude due to electron-electron scattering is around 3.5 mm at the injection point with β_x of 23 m. In the above parameter range, we don't see the clear dependence on the strength distribution.

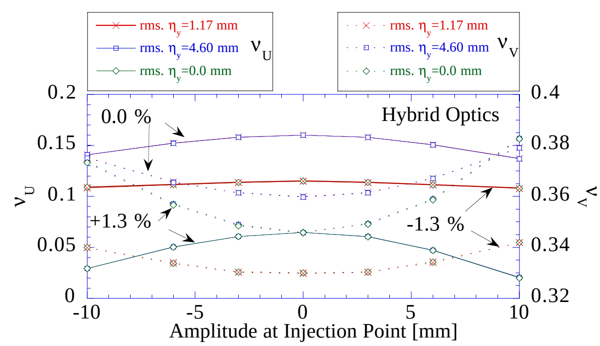

Figure 3: Amplitude-dependent tune shift (Hybrid optics)

In Fig.4, we show the calculated amplitude-dependent tune shift for the HHLV optics with the same parameters as in Fig.3. The relative momentum deviation is set to the measured momentum acceptance, ± 2 % and at this acceptance the maximum oscillation amplitude due to the scattering is around 7.5 mm at the injection point. We see that the small difference appears in the region where the momentum deviation is +2% and the amplitude is beyond 7mm.

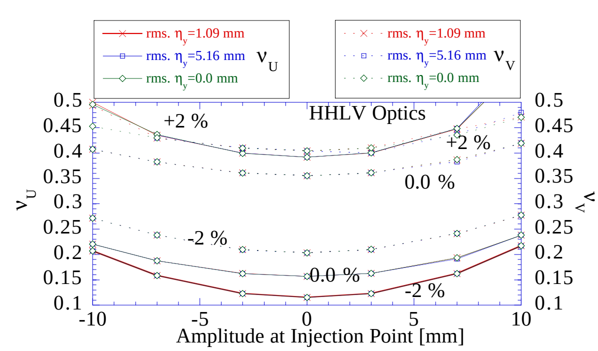

Figure 4: Amplitude-dependent tune shift (HHLV optics)

In Fig.5, we show the calculated distortion of vertical betatron function for the HHLV optics. We see that the distortion is small, less than ~0.05% in the full tuning range of skew quadrupole strength. This means accidental integer and half integer resonance is not excited during the measurement.

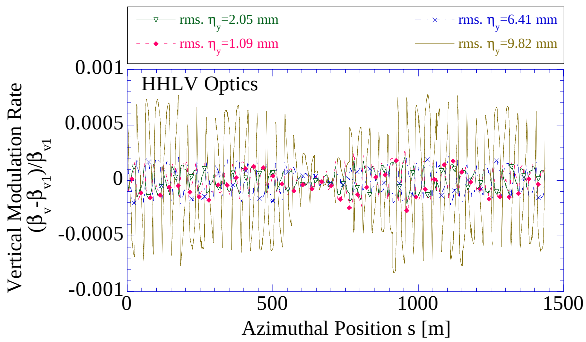

Figure 5: Distortion of vertical betatron functions

In the HHLV optics, the large momentum deviation occasionally raises the coupling oscillation depending on the strength distribution of skew quadrupoles. It is thus important to measure the beam lifetime with a bare ring having large physical aperture in a vertical direction. In the SPring-8 storage ring, minimum vertical aperture is 15 mm. At this position β_y is 3.9 m so that this vertical aperture doesn't limit the momentum acceptance.

5 EXPERIMENTS

We used 11 sets of the skew quadrupole strength distributions, p1 ~ p11 to change the vertical dispersion by 0.5 ~1.0 mm step in an rms. value and measured beam lifetime for two kinds of optics (HHLV and Hybrid). Used beam filling is 1mA×21bunches where Touschek effects is dominant in the beam loss mechanism. All ID gaps were fully opened and RF voltage was set to 12 MV to keep the RF bucket height low. 24 skew quadrupoles are used to change the vertical dispersion distribution.

Measured vertical dispersion for the HHLV optics is shown in Fig.6. Here, the set of p6 gives the natural vertical dispersion with all skew quadrupolesturned off.

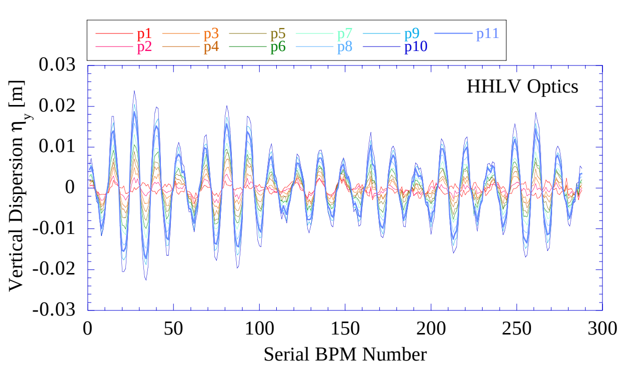

Figure 6: Vertical dispersion distributions

6 ESTIMATION OF VERTICAL EMITTANCE

Measured natural vertical dispersion is reproduced with the computer model with 144 skew quadrupole error sources along the ring. And then, the strength distributions used in the experiment are superimposed on the constructed model to reproduce other dispersion distributions. Except for the distributions with smaller rms. values, model distributions have good agreement with experimental data within rms. error of several %. In Fig.7, the measured natural dispersion distribution is shown together with that calculatedby the model.

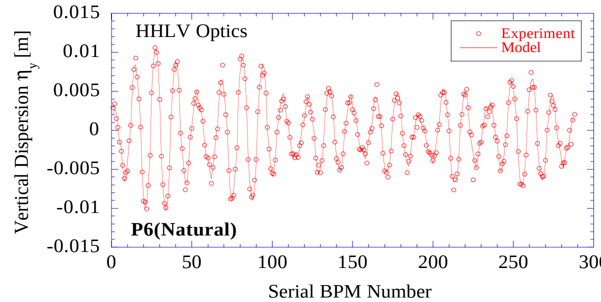

Figure 7: Comparison between model dispersion and experimental data

By using the computer models describing 11 experimental conditions p1 ~ p11 and Eq. (3), we can estimate ε_{y_c} and ε_{y_r} at each condition. In Fig.8, we show measured beam lifetime as a function of the excitation parameter, together with the fitting results. The horizontal error bar includes estimation errors of both betatron and dispersion functions and model fitting errors and vertical one shows a beam lifetime fitting error. As seen in Fig.8, measured data are well fitted by Eq. (3). In the nominal condition p6, vertical emittance values for HHLV and Hybrid optics are estimated to be respectively 5.5 (ε_{y_c} =4.2, ε_{y_r}. =1.3) and 5.1 (ε_{y_c} =3.2, ε_{y_r}. =1.9) pm.rad.

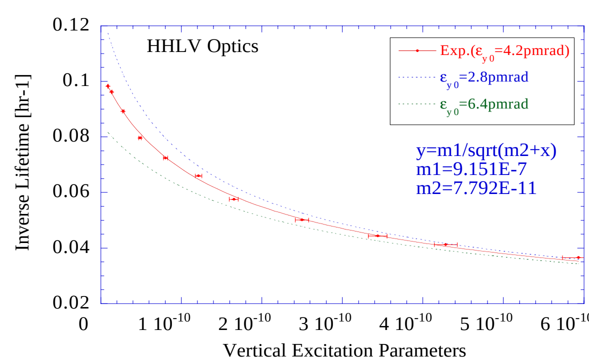

Figure 8: Measured and fitted beam lifetime

REFERENCES

[1] N. Kumagai et al., Proc. 1999 PAC, NY, p.2349.