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EXPERIENCE WITH ROUND BEAM OPERATION AT THE ADVANCED PHOTON SOURCE *

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Abstract

Very short Touschek lifetime becomes a common issue for next-generation ultra-low emittance storage ring light sources. In order to reach a longer beam lifetime, such a machine often requires operating with a vertical-to-horizontal emittance ratio close to an unity, i.e. a "round beam". In tests at the APS storage ring, we determined how a round beam can be reached experimentally. Some general issues, such as beam injection, optics measurement and corrections, and orbit correction have been tested also. To demonstrate that a round beam was achieved, the beam size ratio is calibrated using beam lifetime measurement.

INTRODUCTION

It is foreseen that the brightness from a next-generation storage ring based light source can be improved by several orders with an ultra-low emittance lattice design. One of the biggest challenges associated with an ultra-low emittance storage ring is the necessarily much shorter beam lifetime. In many cases, the lifetime is so short that the beam can only satisfy operational requirements under a "round beam" operation scenario. A good example of how the beam lifetime varies with beam size ratio can be seen from the proposed APS upgrade MBA lattice design [1], and is illustrated in Fig. 1.

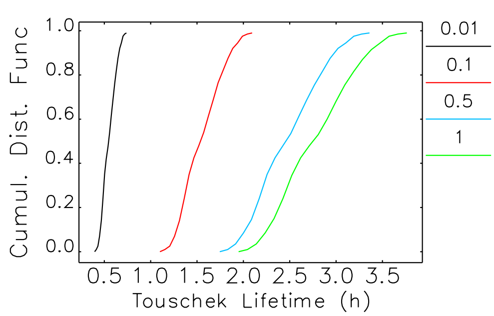

Figure 1: Cumulative distribution functions for the Touschek lifetime from the 100 error ensembles of H7BA optics at different emittance ratios (legend).

A round beam can be achieved in two ways. One is introducing strong skew quadrupoles in the lattice. This method not only couples the x and y beam motion, but also couples optical functions. This scheme could generate difficulty for routine machine operations procedures such as orbit correction, optics measurement and correction, etc. Another way to obtain a round beam is to operate machine at the difference resonance (equal fractional betatron tunes). This way, the coupling coefficient does not need to be large; real machine imperfections with weak skew elements installed in the ring could be enough. Thus the beam operation will be close to a normal decoupled regime of operation, and the x and y optical functions can still be treated separately. The x and y moments (from random process of synchrotron radiation) would simply exchange their values internally due to the resonance effect.

To test the idea of a round beam generation and related operational issues at the coupling resonance, experiments had been performed at the APS storage ring, and results are compared with simulation for the calibrated machine model [2]. We had measured beam lifetime, off-axis injection efficiency, optical response matrix, etc. at different machine coupling coefficients. Beam emittances are calculated from beam sizes measured using dipole synchrotron radiation. The existing vertical beam size measurement system is configured for measurement of only small beam sizes, and does not respond to the round beam conditions that we need to confirm. Thus we used Touschek lifetime at lowered rf voltage to estimate the vertical beam size.

SIMULATION STUDY ON COUPLING RESONANCE

A simple theory for weak betatron coupling can be found in [3]. Assuming that a particle is excited in the x plane, the presence of coupling will cause an interchange of the oscillation energy between the two planes, as shown in Fig. 2. The interchange period T and modulation factor S are given by

$$T = \frac{1}{f_{\mathrm{rev}}\sqrt{\Delta^2 + |C|^2}}, \quad (1)$$

$$S = \frac{E_T}{E_{max}} = \frac{|C|^2}{\Delta^2 + |C|^2}, \quad (2)$$

where f_{rev} is particle's revolution frequency, $\Delta = (\nu_x - \nu_y)$ is separation of uncoupled tunes, and $|C|$ is the machine coupling coefficient, which indicates the strength of the x-y coupling. From Eq. 2 a full x-y energy modulation (round beam) can be reached when $\Delta = 0$. In a real machine, Δ can not be made exactly zero for many reasons, such as tune spread inside the bunch, PS noise, etc. Therefore, we need to test that the round beam can be reached when $\Delta^2 \ll |C|^2$.

Thus the allowable Δ variation range for keeping S above a certain level (for example, $S > 0.9$) depends on $|C|$. If $|C|$ is large, then machine tolerances on various errors are also large, and the oscillation energy is interchanged between x

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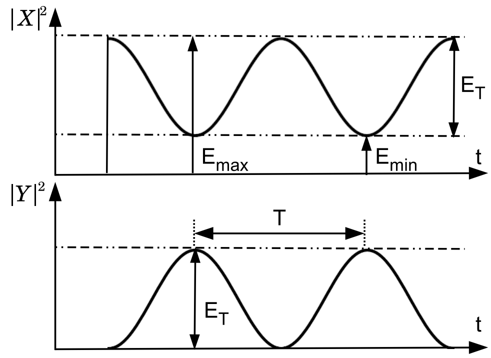

Figure 2: Behavior of the envelope functions of the coherent oscillations following a kick in one plane.

and y rapidly (shorter period T). This condition is reached by introducing strong skew quadrupoles in the lattice, as mentioned before. This has many disadvantages: the x and y optical functions might no longer be separated; the current beam-measurement analysis tools and correction methods, which have been developed over past decades for weak coupling machines, might no longer be valid or will have large errors. Thus new tools would need to be developed or the machine will be more difficult to tune or both.

Recognizing that the above should be avoided, $|C|$ only needs to be set greater than a certain level to allow a reasonable Δ range that can be experimentally reached. The APS storage ring is used as our simulation example for targeting an emittance ratio $\varepsilon_y/\varepsilon_x$ greater than 0.9 for different $|C|$ conditions. We will determine the allowed Δ using `elegant` [4] simulations.

We start with defining κ as the reference emittance ratio at a reference working point of $\nu_x = 0.17$, $\nu_y = 0.23$. We assume that we can adjust skew quadrupoles to acheive any value of $\varepsilon_y/\varepsilon_x$ at the reference working point. For various values of κ the quantity $\varepsilon_y/\varepsilon_x$ is plotted as a function of Δ in Fig. 3. To obtain $\varepsilon_y/\varepsilon_x > 0.9$ the range in Δ will be 0.0016 for $\kappa = 0.01$, 0.0064 for $\kappa = 0.05$ and 0.0092 for $\kappa = 0.10$. That is, the tolerance range in Δ increases with κ, as expected. APS operation shows that $\Delta \leq 0.005$ is easily reachable, thus to obtain a round beam κ needs to be set to ≈ 0.05, which is a weak coupling machine.

Another way to express the strength of x-y coupling either in `elegant` simulations or experimentally is the ratio of the rms orbit in the non-kicked plane v to the rms orbit in the kicked plane u, i.e.

$$g = \sqrt{\frac{\sum_{i_u,j_v} v^2}{\sum_{i_u,j_u} u^2}}, \tag{3}$$

where u can be x or y, v the other plane, i the index of correctors, and j the index of BPMs. Summations are made over all correctors and all BPMs over the ring. When g equals zero, there is no x-y coupling; $g \approx 1$ corresponds to full coupling. A small g indicates that horizontal and vertical orbit corrections can be treated separately. Calculated g values for cases shown in Fig. 3 are listed in Table 1.

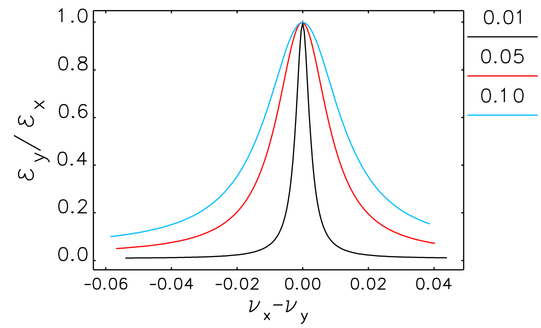

Figure 3: Calculated beam respect ratio ($\varepsilon_y/\varepsilon_x$) vs. tune separation ($\nu_x - \nu_y$) at different coupling κ (legend) for APS.

Table 1: Calculated g Values for Different κ and Δ

κ	$\Delta = -0.05$	$\Delta = 0.0$
0.01	0.023	0.031
0.05	0.051	0.059
0.10	0.069	0.079

EXPERIMENTAL TESTING OF ROUND BEAM OPERATION

As discussed in the previous section, a round beam can be obtained by operating machine close to the coupling resonance. This idea and some practical issues, such as injection efficiency, orbit correction, width of stable working region, were tested at the APS storage ring. Starting from the normal operating APS optics ($\nu_x = 0.17$, $\nu_y = 0.23$), we moved x and y tunes towards each other and measured tunes, beam size, beam lifetime, injection efficiency and the response matrix. This was done for different initial emittance ratios (κ) of 1.0%, 3.0% and 6.0%, achieved by changing skew quadrupoles. Some results are shown in Figures 4 and 5. The vertical beam size measurement was saturated due to our pin-hole camera configuration, so the beam aspect ratio could not be obtained directly. To confirm that a round beam was reached, the lifetime at low rf voltage

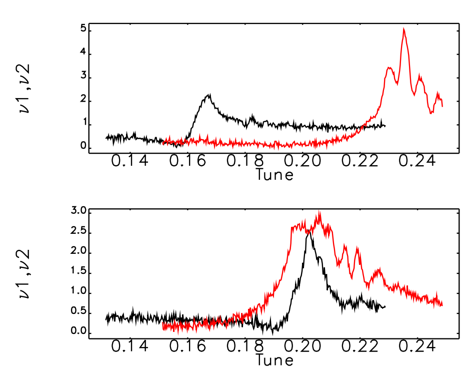

Figure 4: Measured tune spectrum at normal operational tunes (top) and at coupling resonance (bottom).

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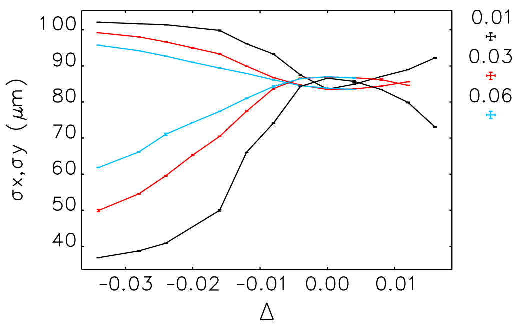

Figure 5: Measured beam size (raw data) and coupling vs. tune separation Δ at different κ (legend).

was used. We reduced the rf voltage to 6.5 MV to make the rf acceptance of $\Delta p/p = 0.01$ (smaller than the nonlinear optics momentum acceptance) and the lifetime is totally Touschek-dominated. Fig. 6 shows the measured beam

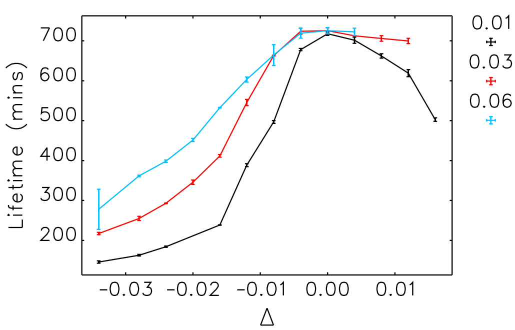

Figure 6: Measured beam lifetime (fitted over 1 min) vs. tune separation Δ at different κ (legend).

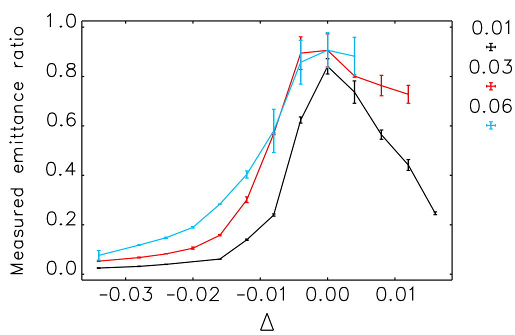

Figure 7: Calculated beam aspect ratio ($\varepsilon_y/\varepsilon_x$) vs. tune separation Δ at different κ (legend). The measured Δ range for $\varepsilon_y/\varepsilon_x \leq 0.8$ is about 0.01 for $\kappa = 0.03$.

lifetime for several scans of tune separation. The beam size ratio is then infered from the measured beam lifetime using program *touschekLifetime*, and is shown in Fig. 7. The injection efficiency (an obvious operational requirement) was also measured and is shown in Fig. 8. We can see that the injection efficiency does not change at all for the emittance ratio of 1%, while it goes down significantly in the vicinity of the coupling resonance for the ratio of 6%. This supports our argument that the round beam is easier to achieve by tuning the machine close to the difference resonance if the natural x-y coupling is low. For a stronger coupled machine, the tuning would be more critical and the stable operational region is limited. Another parameter that characterizes the

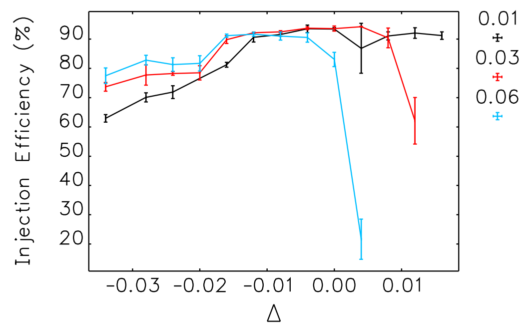

Figure 8: Measured topup injection efficiency vs. tune separation Δ at different κ (legend).

machine operation is the g factor in Eq. 3. A measured g is given in Table 2. We can see that the response matrices remain decoupled.

Table 2: Measured g Value at Different κ and Δ

κ	$\Delta = -0.08$	$\Delta = 0.0$
0.01	0.083	0.091
0.06	0.091	0.096

CONCLUSIONS

A strong particle scattering and short beam lifetime is expected for the future ultra low-emittance light sources. To increase beam lifetime, a round beam operation might be required. Operating machine at a coupling resonance seems the easiest way to reach the round beam operation. This approach has been confirmed through simulation study and beam tests at the APS storage ring. Our measurement results show that good injection efficiency and orbit correction (g value) can be achieved for the round beam conditions with reasonably small x-y coupling when tunes are close to the coupling resonance.

REFERENCES

[1] M. Borland et al., *TUPJE063, Proc. of IPAC'15*.

[2] V. Sajaev., Private Communication.

[3] P. J. Bryant., CERN-94-01, CERN (1994).

[4] M. Borland., ANL/APS LS-287, Advanced Photon Source (2000).