ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK018

ROUND BEAM STUDIES AT NSLS-II*

Y. Hidaka†, W. X. Cheng, Y. Li, T. Shaftan, G. Wang,
Brookhaven National Laboratory, Upton, NY 11973 USA

Abstract

Instead of typical flat beam, some synchrotron light users prefer round beam, i.e., with equal horizontal and vertical emittance, for various reasons (e.g., simplified optics, smaller fraction of photons getting discarded, better phase space match between photon and e-beam). Several future upgrade storage rings such as APS-U, ALS-U, and SLS-2 currently plan to operate in round beam mode. We report our beam study results on round beam operating at NSLS-II by driving linear difference coupling resonance.

INTRODUCTION

Typical synchrotron light sources have been operating in horizontally elongated flat beam for decades. As newer light sources aim to further increase brightness, i.e., reduce emittance down to diffraction limit, beam lifetime becomes shorter and intrabeam scattering (IBS) effect becomes stronger. At some point, there will be no benefit to retain the traditional flat beam. Round beam is a natural choice for such advanced storage rings such as APS-U [1], ALS-U [2], and SLS-2 [3] to overcome these challenges. As another benefit of round beam, some beamline experiments like diffractive imaging utilize round pinholes that would discard many photons if not round [4]. Round beam is also advantageous in that it allows better photon-electron phase space matching, which results in brighter photon beam [5].

Round beam has been recently tested by operating at linear coupling resonance at APS [6]. We employed the same method to demonstrate round beam at NSLS-II, mostly focusing on lattice parameters that prevent beam from reaching full round state.

EXPERIMENTAL RESULTS

All the tune scan experimental data presented in this paper were performed for the nominal NSLS-II bare lattice, i.e., with all insertion devices (IDs) opened, except for adjustment of tunes and chromaticities. The nominal parameters of the lattice are shown in Table 1.

For the purpose of scanning tunes around linear coupling resonance, we utilized special horizontal bumps generated by fast correctors. Unlike quadrupoles, these fast correctors are free from hysteresis effect, which makes the method very reproducible. However, because the fast correctors were not originally intended to be used for this purpose, and the maximum kick strength is only 15 urad, the range of tune change is limited to $\sim \pm 5 \times 10^{-3}$. The unperturbed (i.e., uncoupled) fractional tune distance from resonance $\Delta \equiv \nu_y - \nu_x - q$ with an integer q and unperturbed tunes ν_x and ν_y in all the experimental plots is estimated from the fast corrector setpoints and defined to be zero where vertical beam size becomes maximum.

Table 1: Nominal Parameters of NSLS-II Bare Lattice

Parameter	Value	Unit
Energy	3	GeV
Revolution period	2.64	μs
Ring tune ν_x, ν_y	33.22, 16.26	
Chromaticity ξ_x, ξ_y	+2, +2	
Transv. damping time $\tau_{x,y}$	55	ms
Horiz. natural emittance ϵ_0	2.1	nm-rad
RMS energy spread δ	5×10^{-4}	

The common initial setup before starting each tune scan involves linear lattice correction, including minimization of coupling and vertical dispersion, using the software tool DTBLOC [7] developed at NSLS-II based on resonance driving terms derived from turn-by-turn (TbT) data.

To control (i.e., add) more coupling, the current of one of the skew quadrupoles in a non-dispersive section was adjusted from the state of minimized coupling. This change in normalized integrated strength of the skew quadrupole is denoted by $\Delta a_2 L$.

Note that $\Delta a_2 L = 0$ does not mean no coupling, but rather the state with coupling minimized as much as possible by the lattice correction tool (typically the minimum tune distance between 1×10^{-4} and 2×10^{-4} can be achieved). In addition, machine drift between the completion of lattice correction and the start of tune scan sometimes resulted in loss of a well-corrected coupling state.

When the minimized coupling state has negligible coupling strength compared to the coupling added by the control skew quad, we can estimate the linear coupling driving term for difference resonance C [8]:

$$C = \frac{1}{2\pi} \oint ds \sqrt{\beta_x(s)\beta_y(s)} \cdot \Delta a_2 L(s) e^{i\left[\phi_x(s) - \phi_y(s) - \frac{\Delta \cdot 2\pi s}{L}\right]}$$

where L is the circumference, and $\beta_{x,y}$ and $\phi_{x,y}$ are the unperturbed beta functions and phases, respectively. Given the beta function values at the location of the selected skew quadrupole, $|C| = 2.63 \times \Delta a_2 L[\mathrm{m}^{-1}]$.

The horizontal and vertical beam sizes measured at the pinhole camera for a three-pole wiggler (3PW) source [9], while varying the tune distance, for the nominal +2/+2 chromaticity lattice, are shown in Fig. 1(a). The corresponding "apparent" vertical emittance is shown in Fig. 1(b), defined as $\mathbb{E}_y = \left\{\sigma_y^2 - \left(\eta_y \delta\right)^2\right\} / \beta_y$ [10], where η_y, δ, and β_y are the vertical dispersion, RMS energy spread, and the unperturbed vertical beta function

* Work supported by U.S. DOE under Contract No. DE-AC02-98CH10886.
† yhidaka@bnl.gov

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK018

at the 3PW, respectively. After lattice correction, these values are close to the design values: $\eta_y = 0$ and $\beta_y = 3.75$ m. Note that with a slight increase in coupling, the peak vertical emittance approaches 1 nm $\sim \epsilon_0/2$, i.e., round beam, but is much smaller with minimized coupling. TbT data also show incomplete x-y energy exchange for minimally coupled cases.

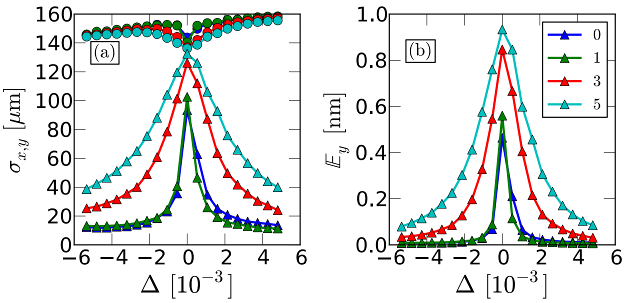

Figure 1: (a) Beam size and (b) apparent vertical emittance at x-ray pinhole camera (from a 3PW source) vs. tune distance from coupling resonance for different coupling strengths $\Delta a_2 L = 0, 1, 3, 5{\times}10^{-4}$ m^{-1}. Circles for horizontal and triangles for vertical beam quantities. ~2 mA in 100 buckets.

One potential reason for this inability to achieve round beam is that simply the peak is missed due to finite tune distance steps. However, scanning around the resonance with very fine tune steps ruled out this possibility. Another possibility is due to tune jitter from magnet power supply noise. The RMS horizontal and vertical tune jitter was measured to be 1.15×10^{-4} and 0.33×10^{-4}, respectively.

However, even without tune jitter, this observation can be explained by a heuristic model of emittance exchange through linear coupling [11, 4] (corroborated by a multi-particle tracking study [12]):

$$\frac{d\epsilon_x}{dt} = -\alpha_c(\epsilon_x - \epsilon_y) - \alpha_x(\epsilon_x - \epsilon_0), \tag{1}$$

$$\frac{d\epsilon_y}{dt} = -\alpha_c(\epsilon_y - \epsilon_x) - \alpha_y \epsilon_y, \tag{2}$$

where ϵ_0 is the natural emittance, and α_x and α_y are the transverse damping rates (=1/55 ms, always fixed in our experiments), while α_c is an effective coupling exchange rate that increases with higher coupling. Setting the right-hand sides of Eqs. (1) and (2) to zero and solving for ϵ_y and ϵ_x yields the equilibrium emittances in the presence of coupling and damping:

$$\epsilon_y = \frac{\alpha_x \alpha_c}{\alpha_c(\alpha_x + \alpha_y) + \alpha_x \alpha_y}\epsilon_0,$$

$$\epsilon_x = \frac{\alpha_x(\alpha_c + \alpha_y)}{\alpha_c(\alpha_x + \alpha_y) + \alpha_x \alpha_y}\epsilon_0.$$

We can see that emittance ratio becomes

$$\frac{\epsilon_y}{\epsilon_x} = \frac{\alpha_c}{\alpha_c + \alpha_y}.$$

It is obvious then that round beam can be achieved only when $\alpha_c \gg \alpha_y$. Being heuristic, no formula exists for this effective rate α_c to our best knowledge. However, it is known from a simple theory for weak betatron coupling [13] that a particle exchanges oscillation energy between x and y planes at the period T

$$T = \frac{1}{f_{\text{rev}}\sqrt{\Delta^2 + |C|^2}},$$

with f_{rev} being the revolution frequency, and achieves full energy modulation when $\Delta = 0$. Thus, we can assume α_c to be on the same time scale as $\alpha_{c0} \equiv 1/T_{\Delta=0} = f_{\text{rev}}|C|$. Then we can represent $\alpha_c = m\alpha_{c0}$ with m being an empirical factor. Figure 2 shows ϵ_x and ϵ_y vs. $|C|$ for m = 1, 3, and 10. At $\Delta a_2 L = 1 \times 10^{-4}\text{m}^{-1}$ (equivalent to $|C| = 2.63 \times 10^{-4}$), the case of m = 10 roughly agrees with the observed ϵ_y of ~500 pm. As coupling increases, ϵ_y rapidly converges to $\epsilon_0/2$.

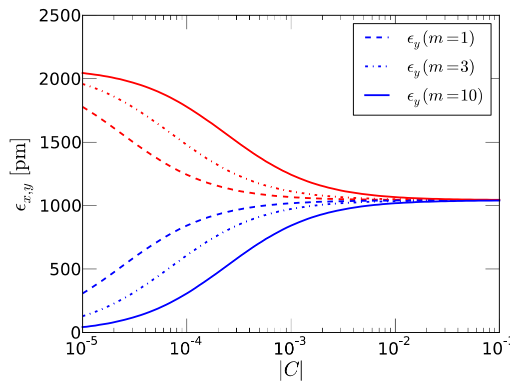

Figure 2: Emittance vs. coupling strength predicted from a heuristic model of transverse emittance sharing.

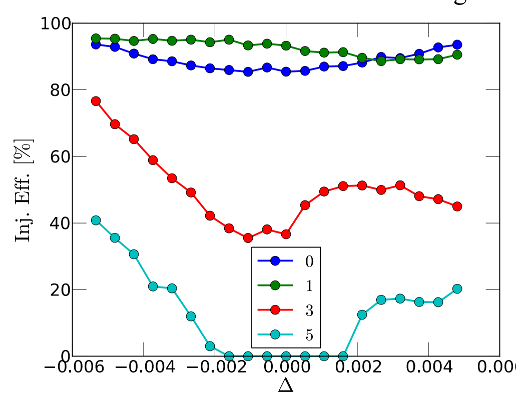

Figure 3: Injection efficiency vs. tune distance from coupling resonance for different coupling strengths $\Delta a_2 L = 0, 1, 3, 5{\times}10^{-4}$ m^{-1}.

From Fig. 1(b), to achieve >90% of ϵ_y for fully round beam for the nominal NSLS-II bare lattice, coupling strength of $|C| = 1.3 \times 10^{-3}$ ($\Delta a_2 L = 5 \times 10^{-4}$ m^{-1}) is required. However, injection efficiency drops rapidly with increased coupling, and to zero at the required coupling level, as shown in Fig. 3. For the NSLS-II damping wiggler lattice used for beamline operation, given its shorter transverse damping time of 24 ms, the required coupling will likely be higher, resulting potentially in worse injection. To avoid this issue, we may need to use the fast correctors to move away from coupling resonance temporarily, as done in the tune scan measurements presented here, during top off injection, although compatibility with

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK018

the fast orbit feedback, transient issues, and insufficient tune adjustment range will need to be addressed. Another solution would be to try a lattice with large amplitude-dependent tune shift, as suggested in [12].

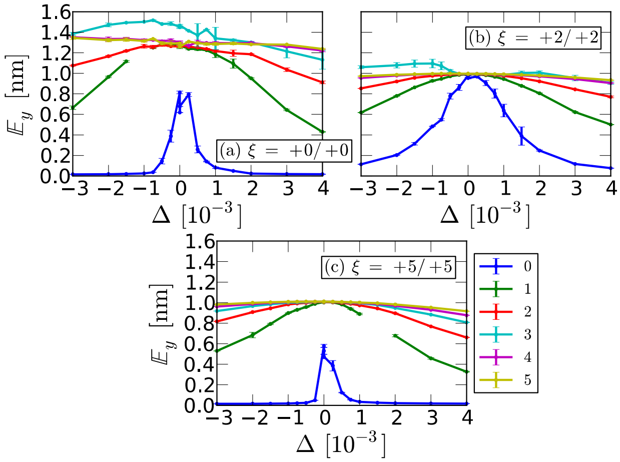

Figure 4: Measured vertical emittance vs. Δ for different coupling strengths $\Delta a_2 L$ = 0, 1, 2, 3, 4, 5×10^{-3} m^{-1} with (a) $\xi = 0/0$, (b) +2/+2, and (c) +5/+5.

We also investigated the effect of tune spread on round beam by adjusting linear chromaticities ξ_x/ξ_y (measured values shown in parentheses) to 0/0 (+0.11/+0.60), +2/+2 (+1.90/+2.25), and +5/+5 (+5.12/+5.11) with ~4 mA in 100 bunches. The experimental results are shown in Figs. 4-6. The RMS tune spread due to finite chromaticity is given by $\sigma_\nu = \xi\delta$ where $\delta = 5 \times 10^{-4}$. With higher ξ, coupling resonance effect may be diluted due to more electrons oscillating at frequencies farther from resonance.

Unfortunately, for the +2/+2 tune scan, a well-corrected coupling state was apparently lost before the scan was initiated, as can be seen from large vertical emittance with $\Delta a_2 L = 0$ at $\Delta = 0$ in Figs. 4(b) and 6(a). This makes it hard to draw a definitive conclusion that smaller vertical emittance with +5/+5 compared to +2/+2 at $\Delta \neq 0$ is caused by larger chromatic tune spread (see Figs. 5(a)-(d)). Some or most of the emittance difference may be attributed to the initial residual coupling error.

Another complication in the obtained data is that the case of $\xi = 0/0$ may be affected by collective effects, as the maximum vertical emittance in all the cases far exceeds the predicted maximum value of 1 nm. This conjecture is further supported by the fact that an attempt to bring ξ_y closer to 0 from +0.6 during a scan setup resulted in sudden increase in beam size at the nominal fractional tunes (0.22, 0.26).

Nonetheless, one unexpected observation was that, for $\xi = +5/+5$, the coupling stopband width $|C| = 2.6 \times 10^{-3}$ for $\Delta a_2 L = 1 \times 10^{-3}$ m^{-1} corresponds to mere $\pm 0.5\sigma_\nu (= \pm 1.25 \times 10^{-3})$. This means only ~38% of the electrons (assuming Gaussian) at a given moment are within the stopband, and yet the measured vertical emittance at $\Delta = 0$ shows that almost fully round beam is achieved. This suggests that round beam operation is likely to be not so sensitive to the choice of linear chromaticity values.

Another surprise was that there appears to be unknown resonance or instability that increases both horizontal and vertical beam sizes with $\Delta a_2 L = 3 \times 10^{-3}$ m^{-1}, as seen in Fig. 6. This phenomenon is not observed for $\xi = +5/+5$, which implies the mechanism may be also related to collective effects.

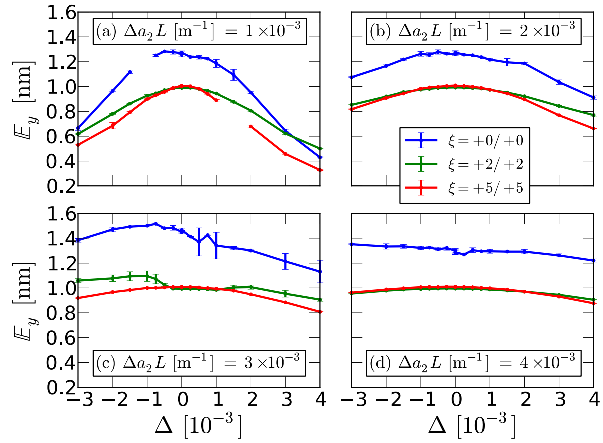

Figure 5: Measured vertical emittance vs. Δ for ξ = 0/0, +2/+2, +5/+5 with $\Delta a_2 L$ = (a) 1, (b) 2, (c) 3, and (d) 4×10^{-3} m^{-1}.

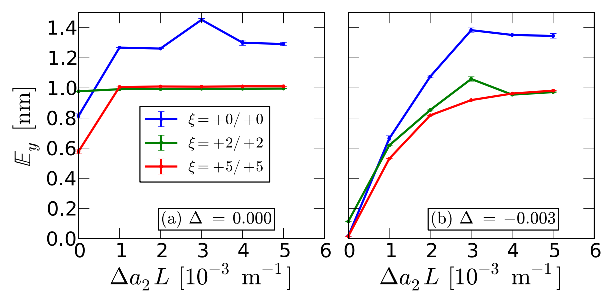

Figure 6: Measured vertical emittance vs. $\Delta a_2 L$ for ξ = 0/0, +2/+2, +5/+5 at (a) $\Delta = 0$ and (b) $\Delta = -0.003$.

CONCLUSION

We have demonstrated round beam at NSLS-II using the nominal bare lattice sitting on linear coupling resonance to obtain insights and potential pitfalls awaiting for future light sources planning to operate in round beam mode. To achieve round beam, coupling had to be increased to compete against damping effect to the point where injection became impossible if the tunes were set directly on resonance. To enable injection with this round beam scheme, other solutions such as temporary tune adjustment and a lattice with large tune shift with amplitude are likely needed. We also experimentally found that coupling resonance is not too sensitive to increased tune spread from higher linear chromaticities.

ACKNOWLEDGMENTS

Y. H. would like to thank B. Podobedov and G. Bassi for useful discussions.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-TUPMK018

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2018). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

REFERENCES

[1] APS-U Preliminary Design Review (PDR) Report: https://www.aps.anl.gov/sites/default/files/APS-Uploads/Aps-Upgrade/Chapter%204%20-%20Accelerator.pdf

[2] C. Steier *et al*., "Status of the Conceptual Design of ALS-U," Proc. IPAC2017, Copenhagen, Denmark, May 2017, pp. 2824-2826, doi:10.18429/JACoW-IPAC2017-WEPAB104

[3] SLS-2 Conceptual Design Report, PSI-Bericht 17-03 (2017).

[4] C. Steier, "Coupling Control and Optimization in DLSRs," High-Brightness Synchrotron Light Source Workshop, Upton, NY, USA (2017).

[5] L. Liu, "Towards Diffraction Limited Storage Ring Based Light Sources," Proc. IPAC2017, Copenhagen, Denmark May 2017, pp. 1203-1208, doi:10.18429/JACoW-IPAC2017-TUXA1

[6] A. Xiao, L. Emery, V. Sajaev, and B. Yang, "Experience with Round Beam Operation at the Advanced Photon Source," Proc. IPAC2015, Richmond, VA, USA, May 2015, paper MOPMA013, pp. 562-564.

[7] Y. Hidaka, B. Podobedov, and J. Bengtsson, "Linear Optics Characterization and Correction Method using Turn-by-Turn BPM Data Based on Resonance Driving Terms with Simultaneous BPM Calibration Capability," Proc. NAPAC2016, Chicago, IL, USA, Oct. 2016, pp. 605-608, doi:10.18429/JACoW-NAPAC2016-TUPOB52

[8] M. Takao, M. Masaki, Y. Shimosaki, K. Soutome, S. Takano, and C. Zhang, "Progress of Emittance Coupling Correction at the Spring-8 Storage Ring," Proc. IPAC2012, New Orleans, LA, USA, May 2012, paper TUPPC016, pp. 1191-1193.

[9] W. X. Cheng, B. Bacha, B. N. Kosciuk, D. Padrazo Jr., "Improvements of NSLS-II X-ray Diagnostic Beamlines," presented at IPAC2018, Vancouver, Canada, Apr.-May 2018, paper WEPAF012, this conference.

[10] A. Franchi, L. Farvacque, J. Chavanne, F. Ewald, B. Nash, K. Scheidt, and R. Tomas, *Phys. Rev. ST Accel. Beams*, vol. 14, p. 034002 (2011).

[11] S.Y. Lee, *Accelerator Physics*, 2nd ed., World Scientific, Singapore p. 464.

[12] P. Kuske, "Review of Methods to Produce Round Beams," Workshop on Round Beams, Paris, France (2017).

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