LONGITUDINAL BEAM PARAMETER TOLERANCES OF NSLS-II

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Abstract

NSLS-II is a third generation light source under design. The beam stability control has been taken into considertion. In this paper we looked into the longitudinal tolerances. We found that the timing and infrared beamlines are the most susceptible to the longitudinal noise. The rest of the beamlines are affected because of the dispersion and the momentum dependent vertical divergence effects. We set a tolerance of $\Delta p/p < 5 \times 10^{-5}$ on the longitudinal energy oscillation amplitude.

INTRODUCTION

NSLS-II is a proposed third-generation light source, which will be the replacement of the existing 29 years old National Synchrotron Light Source. The storage ring is designed to have 30 double-bend-achromatic cells with 15 fold symmetry. The emittance of the bare lattice is 2 nm, and it will be reduced to below 1 nm by the damping wigglers. The vertical emittance will be 8 pm, which is the diffraction limit for 1 Angstrom radiation.

The beam stability control has been incorporated into the design[1]. The general requirement is that the beam jitter amplitude should be no more than 10% of the beam size. This corresponds to 0.3 μm vertically and 5 μm horizontally in the short undulator straight section. To meet this goal, tolerances have been set on the power supply ripple, floor motion, and girder vibration. Orbit feedback loop will be used to stabilize the transverse jitter. The longitudinal stability is controlled by the lower level rf system. In this paper we discuss the tolerances on the longitudinal parameters.

In the longitudinal phase space the fundamental parameters are: bunch arrival time(or the corresponding RF phase), average momentum, bunch length, and momentum spread. These parameters are perturbed by various noise sources in a real machine. The noise could excite longitudinal bunch motion, seen by the users as time or transverse position jitter,and intensity variation. The longitudinal oscillations cause longitudinal emittance growth, lengthening the bunch and increasing the momentum spread, and decreasing the brightness by enlarging the vertical divergence. Both the longitudinal oscillation and the emittance growth are related to the stability issues. To be consistent, we also impose a tolerance of 10% on the photon beam size.

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LONGITUDINAL OSCILLATION AND DECOHERENCE

In the longitudinal phase space, the conjugate variables are $(\Delta\phi, \Delta p/p)$, where $\Delta\phi$ is the relative rf phase, and $\Delta p/p$ is the momentum offset. If there is an oscillation in momentum, there will be a corresponding phase jitter. The relation between the amplitudes is given by

$$\Delta\phi = \frac{h\alpha_c}{\nu_s}\Delta p/p, \tag{1}$$

where $h \approx 1300$ is the rf harmonic number, $\alpha_c = 3.7 \times 10^{-4}$ is the momentum compaction factor. For $V_{rf} = 5$MV, the longitudinal tune $\nu_s = 0.011$. Therefore $\frac{h\alpha_c}{\nu_s} = 43.7$. Some other relevant longitudinal parameters are $\sigma_\delta = 1 \times 10^{-3}$, and $\sigma_t \sim 15$ps.

If the oscillation is not corrected, it will decohere in the longitudinal phase space and cause emittance increase. Now we calculate the emittance growth rate as a function of the initial oscillation amplitude. Given a momentum kick $\Delta p/p$, an individual particle will have a longitudinal oscillation

$$\delta(t) = (\Delta p/p)\sin\nu_s\omega_0 t + \delta_0 \sin\nu_s\omega_0(t + t_0), \tag{2}$$

where ν_s is the longitudinal tune, ω_0 is the angular revolution frequency, t is time, and (δ_0, t_0) are the initial coordinates. After sufficient long time (greater than the longitudinal oscillation period, but less than the longitudinal damping time), the oscillation can be described by

$$\delta(t) = \Delta p/p \sin\nu_s\omega_0(t + t_1) + \delta_0 \sin\nu_s\omega_0(t + t_2), \tag{3}$$

where t_1 and t_2 are different for different particles due to the tune spread. However, for all the particles in a bunch, t_1 and t_2 are uniformly distributed in $[0, 2\pi]$. Averaging over t_1, t_2 and δ_0, one gets

$$\sigma_\delta = \sqrt{\frac{1}{2}(\frac{\Delta p}{p})^2 + \sigma_{\delta,0}^2} = \sigma_{\delta,0}\sqrt{1 + \frac{1}{2}f^2}, \tag{4}$$

where $f = (\Delta p/p)/\sigma_{\delta,0}$ is the initial relative kick amplitude. If the sampling time scale is much shorter than the synchrotron period, then the worst instantaneous momentum spread is[2]

$$\sigma_{\delta,eff} = \sigma_{\delta,0}\sqrt{1 + f^2}. \tag{5}$$

MOMENTUM DEPENDENT VERTICAL DIVERGENCE

The majority of users exploit the x-rays from the undulators, which are located in the zero dispersion straight sections. Hence they are not affected by the horizontal motion induced by the momentum jitter. However, the vertical photon beam size is affected by the longitudinal phase space parameters, like the momentum spread[3]. To illustrate this, we start from the wave length of the photons radiated from an insertion device

$$\lambda_n = \frac{\lambda_u}{2n\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta_n^2), \tag{6}$$

where λ_n is the wavelength of the nth harmonic, λ_u is the period length of the ID, K is the deflection parameter, γ is the relativistic factor, and θ_n is the opening angle.

Solving for θ_n, one gets

$$\theta_n^2 = \frac{2n\lambda_n(\theta_n)}{\lambda_u} - \frac{1+\frac{K^2}{2}}{\gamma^2}. \tag{7}$$

Now expand the right hand side for the energy spread

$$\begin{aligned}\theta_n^2 &= \frac{2n\lambda_n(\theta_n)}{\lambda_u} - \frac{1+\frac{K^2}{2}}{\gamma_0^2}(1-2\frac{\Delta\gamma}{\gamma}) \\ &= \frac{2n\Delta\lambda_n}{\lambda_u} + \frac{4n\lambda_n(0)}{\lambda_u}\frac{\Delta\gamma}{\gamma} \\ &= \frac{2n\lambda_n}{\lambda_u}(\frac{\Delta\lambda_n}{\lambda_n} + 2\frac{\Delta\gamma}{\gamma}) \end{aligned} \tag{8}$$

where $\Delta\lambda_n = \lambda_n(\theta_n) - \lambda_n(0)$ and $\Delta\gamma/\gamma$ is the fractional energy offset. Therefore the opening angle depends on both diffraction and momentum spread. From simulation we found that when $nN\sigma_\delta < 1$, the following expression gives a good approximation of σ_θ:

$$\sigma_\theta^2 \approx \sqrt{\langle\theta^4\rangle} = \frac{\lambda_n}{L}\sqrt{1+16n^2N^2\sigma_\delta^2}, \tag{9}$$

where L is the length of the ID, N is the number of periods, and σ_δ is the RMS momentum spread. And the relation $\langle(\frac{\lambda_n}{\lambda_n})^2\rangle = \frac{1}{2nN}$ has been used. Using some typical numbers for NSLS II, such as $\sigma_\delta \sim 10^{-3}$, and with $n = 2$ and $N = 100$, one finds that the second term in the square root equals 0.64. Because of the n square dependence, the opening angle of the higher harmonics ($n > 3$) is dominated by the momentum spread. In that case

$$\sigma_\theta^2 = \frac{4\lambda_1}{\lambda_u}\sigma_\delta, \tag{10}$$

which is independent of the harmonic number n. With $\lambda_1 = 1\mathring{A}$, $L = 3$ and $N = 100$ one gets $\sigma_\theta^2 = 1.3 \times 10^{-11}$.

Note the source size is

$$\sigma_r = \sigma_\theta\frac{L}{2} = \frac{\sqrt{\lambda_n L}}{2}(1+16n^2N^2\sigma_\delta^2)^{1/4}. \tag{11}$$

Therefore both the divergence and the source size are blown up due to the momentum spread.

Including the vertical emittance, and bearing in mind that $\sigma_\theta^2 = \sigma_{X'}^2 + \sigma_{Y'}^2$, so $\sigma_{Y'}^2 = \frac{1}{2}\sigma_\theta^2$, one gets the divergence of a photon beam

$$\sigma_{Y'}^2 = \frac{\lambda_n}{2L}\sqrt{1+16n^2N^2\sigma_\delta^2} + \epsilon_y/\beta_y, \tag{12}$$

where β_y and ϵ_y are the vertical beta function and vertical emittance of the electron beam, respectively. For NSLS II, $\epsilon_y \sim 8 \times 10^{-12}$m·Rad, $\beta_y \sim 1$m, one finds $\frac{2\lambda_1}{\lambda_u}\sigma_\delta \sim 6.7 \times 10^{-12}$, which is comparable to ϵ_y/β_y. Fig.1 shows the vertical divergence for harmonic numbers 1-9.

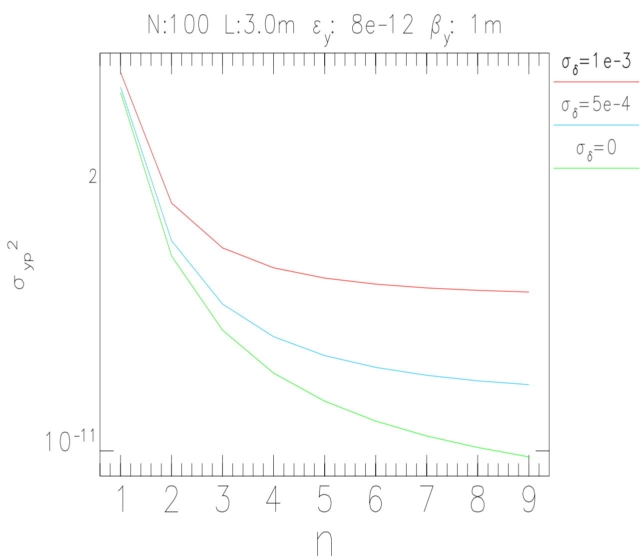

Figure 1: The vertical divergence as a function of harmonic number. Three values of σ_δ are plotted. For the nominal momentum spread $\sigma_\delta = 1 \times 10^{-3}$, the vertical divergence starts to saturate at the 5th harmonic.

USER REQUIREMENTS

The users are concerned about the longitudinal beam parameters in several ways. The major concerns are: timing jitter caused by the longitudinal centroid oscillation, transverse position jitter at nonzero dispersion region, and beam size increase due to the momentum dependent vertical divergence. These effects are discussed in the following.

The momentum dependent vertical divergence affects almost all the users. If the photon beam is not focused, the final spot size is proportional to $\sigma_{Y'}$ given in Eq.(12). On a focusing beamline, the photon beam size is determined by the source size, as is presented in Eq.(11). In either case, the brightness is inversely proportional to $\sqrt{\sigma_\delta}$ for the higher harmonics. If the measurement takes much longer than a synchrotron period, according to Eq.(4), an initial momentum noise of $\Delta p/p = 1.3 \times 10^{-3}$ would cause a 10% increase in momentum spread due to either decoherence or averaging. For the short time measurements, the brightness is affected by the instantaneous oscillation. From Eq.(5), we calculated $\Delta p/p < 9 \times 10^{-4}$ is needed to meet the 10% tolerance.

Next the timing jitter affects the timing-dependent experiments. The users from this category ask for a timing jitter tolerance to be 5% of the RMS bunch length at frequencies above 500 Hz. Jitters at lower frequencies can be tracked by the x-ray users. 5% of a 15 ps bunch corresponds to a phase error of $\Delta\phi = 0.135°$ in a 500 MHz rf system. According to Eq.(1), the equivalent momentum jitter limit is $\Delta p/p = 5 \times 10^{-5}$.

The measurements using infrared radiation have proven to be very sensitive to the longitudinal oscillation [4]. First they are very sensitive to the source motion because of the long wave length; second the synchrotron frequency is in the range of interest. For example, 2.5 to 3 kHz was found most troublesome in reference [4]. Third the infrared radiation is usually taken from a dipole magnet, where the dispersion is nonzero. At Advanced Light Source an energy noise oscillation of 3×10^{-5} was detected at their infrared beamlines [5]. Even though some users desire an even tighter tolerance, we set an achievable momentum tolerance of $\Delta p/p = 5 \times 10^{-5}$ for frequencies greater than 500 Hz, the same as that for the timing users. Note for a location with 5cm dispersion, the horizontal motion would be limited to 2.5 μm, which is less than 5% of the horizontal beam size.

The beam size of some of the beamlines at the NSLS-II is dominated by the dispersion, such as the dipole beamlines and three-pole wiggler beamlines. For those beamlines, momentum jitter induces horizontal position jitter. The 10% rule requires the momentum jitter to be $\Delta p/p < 1 \times 10^{-4}$. The beam size is proportional to the momentum spread. From Eq.(4) and Eq.(5), we found the momentum oscillation should be less than 6.5×10^{-4} for long time measurements and 4.6×10^{-4} for the short time measurements. Consequently for these beamlines the tolerance is $\Delta p/p = 1 \times 10^{-4}$, which is from the position stability requirement. Many experiments have a stringent requirement on the horizontal angle stability. The minimum tolerance is about 1 μrad. Because the derivative of dispersion $\eta' \sim 0.1$, 1 μrad requires $\Delta p/p < 1 \times 10^{-5}$, which is too small to realize. Experiments require 1 μrad stability must use the zero-dispersion straight.

Another effect is due to the residual dispersion. As is mentioned earlier, the straight sections of NSLS-II are designed to be zero dispersion. However, due to lattice errors there will be residual dispersion. The order of magnitude is about 1 mm, same for the vertical and horizontal directions. The vertical beam size is much smaller, therefore, the limit will come from the vertical plane. In the vertical direction, $\sigma_y = \sqrt{\epsilon_y \beta_y + \eta_y^2 \sigma_\delta^2}$. Because the second term in the square root is much less than the first term, the momentum spread change is not going to cause a notable change in the vertical beam size. However, the vertical position $y = y_0 + \eta_y \langle\delta\rangle$. The allowed centroid jitter is 10% of the beam size, or, 0.3μm; therefore the average momentum jitter should be less than 3×10^{-4}.

CONCLUSION

As a summary, Table 1 lists the requirements on the longitudinal beam parameters from different user groups.

The tightest requirement is from the timing and IR users,

Table 1: Longitudinal beam stability requirements for NSLS-II

	$\Delta\phi$(°)	dδ($\times 10^{-4}$)
Timing, IR	0.14	0.5
Vertical divergence	2.4	9
Dipole beamlines	0.27	1
Residual dispersion	0.81	3

who require a phase jitter of less than $0.14°$ or equivalent momentum jitter $< 5 \times 10^{-5}$. Fortunately this is within the capability of the present technology[6]. We will be following the development in the field of RF feedback and control and design our system with consideration of physics requirements, cost and available technologies.

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