STUDY OF BEAM EMITTANCE AND ENERGY SPREAD MEASUREMENT USING SVD AND MULTIPLE FLAGS IN THE NSLS-II BOOSTER EXTRACTION BEAMLINE*

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Abstract

The low beam emittance requirement in the NSLS-II storage ring imposes a very tight constraint on its acceptance. This requires the injected beam emittance to be very small. Therefore, we need a reliable scheme to measure the emittance and momentum spread of the beam coming out the booster. The original scheme based on the booster-to-dump transport line is hampered by the difficulty in decoupling emittance from energy spread. This paper will describe a method being planned to use the booster extraction line to measure the beam emittance and energy spread, as well as the associated errors.

INTRODUCTION

The NSLS-II is a 3 GeV third generation synchrotron light source under construction at Brookhaven National Lab. The storage ring low beam emittance requirement imposes a serious consideration of the injected beam quality. The booster emittance may impact the injection efficiency.[1] It is required to deliver 80~150 bunches in a bunch train with 10 nC circulating bunch charge at a repetition rate of 1 Hz and a horizontal beam emittance of 40 nm-rad. During extraction from booster, the beam loss is required to be less than 20% and the beam emittance blowup is less than 20%.

To extract the bunch train from booster during one turn, the extraction kicker needs to build up field fast and maintain a wide flat top waveform. This is very difficult within < 200 ns rise time. Any ripple or droop of the extraction kicker in the bunch train will increase the measured beam emittance.

The booster to dump transport line will be used to study the beam properties from booster in commissioning stage and beam studies. In this paper, we describe the method to measure the beam emittance and energy spread with an SVD method to improve the measurement accuracy. [2] Its advantage is proven in keeping the measurement data accuracy with least number of optics changes. We also discuss our transport line transfer matrix measurement.

TRANSPORT LINE LAYOUT

The booster to dumper transport line, as shown in Figure 1, will be used to measure the beam parameters from booster. There are four flags, composed of an OTR and a YAG screen for the beam size and position measurement labelled as black box in Figure 1. There is a Fast Current Transformer to measure the fill pattern, an Integrating Current Transformer to measure the bunch train current and a Faraday Cup incorporated with the dump to monitor the charge deposit at dump.

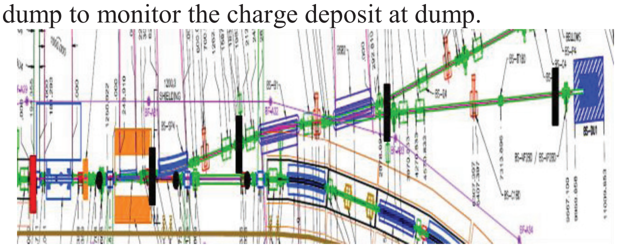

Figure 1 Booster to dump transport line layout

The booster extraction system consists of four slow orbit bumps, an extraction kicker, a short weak pulsed septum and a long strong DC septum. The orbit of the circulating bunch train is slowly moved out toward the septum by slow orbit bumps in 2000 turns and is kicked into the extraction septum by the one turn extraction kicker. The second dipole magnet is used to switch the beam between the transport line to dump and the transport line to storage ring.

Usually, energy spread measurement and emittance measurement are separated in a dispersion region and an achromatic region. There is no way to suppress the dispersion in the transport line due to space constraints. And the β function and dispersion function contribute to the beam size are comparable. So the energy spread and emittance measurements are always coupled. Here we use multi-screen, multi-optics and SVD method to measure them together. [3]

THEORY

The measured beam size S_x at a flag can be written as

$$\sigma = S_x^2 = M_{11}^2\,(\beta_0\varepsilon) - 2\,M_{11}M_{12}\,(\alpha_0\varepsilon) + M_{12}^2\,(\gamma_0\varepsilon) + D^2\langle\delta^2\rangle \quad (1)$$

Equation 1 is the beam profile propagation from a reference point "O" to the flag. $\beta_0, \alpha_0, \gamma_0$ are the twiss parameters at "O", ε is the rms beam emittance, $\langle\delta^2\rangle$ is the rms energy spread. M_{ij} (i,j=1,2) is the transport matrix element from "O" to the flag, and D is the dispersion at the flag.

In our case, we want to fit the Twiss parameters, emittance and energy spread at the reference point by measuring the beam size at different flags along the transport line. These fitted parameters do not change

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during the measurement. Beam sizes can be written as matrix equation 2. The transport matrix changes either due to flags location difference or the optics set change, such as quads scan.

$$\begin{pmatrix}\sigma^1\\ \vdots\\ \sigma^N\end{pmatrix} = R.o = \begin{pmatrix} M_{11}^2(1) & -2\,M_{11}(1)M_{12}(1) & M_{12}^2(1) & D^2(1)\\ \vdots & \vdots & \vdots & \vdots\\ \vdots & \vdots & \vdots & \vdots\\ M_{11}^2(N) & -2\,M_{11}(N)M_{12}(N) & M_{12}^2(N) & D^2(N)\end{pmatrix}\begin{pmatrix}\beta_0\varepsilon\\ \alpha_0\varepsilon\\ \gamma_0\varepsilon\\ \langle\delta^2\rangle\end{pmatrix} \quad (2)$$

The index 1 through N refers to different measurements. N should be larger than the fitted parameters number.

By inverting the equation (2) using SVD, we can get the unknown parameters, which are $\beta_0\varepsilon$, $\alpha_0\varepsilon$, $\gamma_0\varepsilon$ and $\langle\delta^2\rangle$.

The singular values of the R matrix reflect the amplification of the error. If the optics are not chosen properly, the singular values of the R matrix could be 0 or very close to 0, so that the above equation has no solution and the measured data is very sensitive to error. The ratio of maximum to minimum singular values of the matrix R indicates the fitted data amplification difference. This value can be used to judge whether the optics set is good.

In our case, the reference point is chosen at the booster extraction point. The designed parameters at this point are listed in Table I.

Table I: Design beam parameters at the reference point

Parameter	Value
$\beta_0\varepsilon$	$5.0\times10^{-7}\ m^2$
$\alpha_0\varepsilon$	$-2.85\times10^{-8}\ m$
$\gamma_0\varepsilon$	6.6×10^{-9}
$\langle\delta^2\rangle$	1×10^{-6}

We can see that, the design parameters vary by a factor of 100. This means the singular values of the R matrix vary by a similar factor of 100, even for optimal optics. Therefore, it is hard to judge the error sensitivity due to the optics with the R matrix.

To avoid this problem, we scale the fitted parameters by their design value. Equation 2 can be rewritten as Equation 3. In this normalized equation, the singular values of the normalized matrix $\hat{R}$ directly reflect the fitted data sensitivity to the error. A good choice of optics should have singular values of similar order.

TRANSPORT MATRIX MEASUREMENT

To fit the beam parameters at the reference point, the transport matrix from the reference point to flags and the dispersion at flags should be known well. In the transport line, we will use the beam based measurement to get these parameters, so that the whole measurement has no assumptions.

The beam trajectory at transport line different position can be correlated by transfer matrix as

$$x_f = M_{11}x_i + M_{12}x_i' + M_{16}\delta_i \quad (4)$$

where x_i, x_i', δ_i are the initial beam position, angle and energy deviation at the reference point, x_f is the resulting beam position at flags. We fit the transfer matrix with different initial trajectories, which should be known well. To do this, there must be at least three known trajectories and these trajectories cannot be degenerate. This means there are at least two correctors with proper phase advance between them and the beam energy should change.

To simplify the transport matrix measurement, the beam position change due to x and x' are separated from its change duo to the beam energy change. The x and x' are generated with correctors. The δ is generated by adjusting the beam extraction energy.

By changing the beam extraction energy change, the transport matrix M_{16} from extraction point to the flags can be measured due to. The dispersion at flag is

$$D = M_{11}D_x^i + M_{12}D_x^{i\prime} + M_{16} \quad (5)$$

where D_x^i and $D_x^{i\prime}$ are the dispersion and dispersion prime at the extraction point. Dispersion at the extraction point can be measured by tuning the RF frequency in the booster.

To measure the matrix M_{11} and M_{12}, four correctors, are selected and work in pairs. The phase advance between each pair is 88 degree. They are robust enough to make a closed bump in booster and control the beam trajectories to the transport line. Along with three BPMs in the booster extraction straight, the beam initial trajectory is well defined. There is only a drift between the three BPMs. This choice has the advantages in that it is not necessary to know the lattice between BPMs and correctors, and the BPM noise can be greatly reduced by averaging many turns BPM data.

Figure 2 shows 10 different closed orbits in booster. The maximum strength of correctors is 0.5 mrad. The closed orbit amplitude in booster is 2mm. The corresponding trajectory amplitude at the extraction point is 0.5mm. With this method, the measured transfer matrix error of M_{11} and M_{12} are 0.09 and 0.09m, where we assume 10 different trajectories, 100 μm flag error, and 1 mrad maximum kicker strength. With large the signal/noise ratio or large numbers of trajectory, the transfer matrix accuracy can be improved.

$$\begin{pmatrix}\sigma^1\\ \vdots\\ \sigma^N\end{pmatrix} = \hat{R}.\hat{o} = \begin{pmatrix} M_{11}^2(1)(\beta_0\varepsilon)_i & -2\,M_{11}(1)M_{12}(1)(\alpha_0\varepsilon)_i & M_{12}^2(1)(\gamma_0\varepsilon)_i & D^2(1)(\langle\delta^2\rangle)_i\\ \vdots & \vdots & \vdots & \vdots\\ M_{11}^2(N)(\beta_0\varepsilon)_i & -2\,M_{11}(N)M_{12}(N)(\alpha_0\varepsilon)_i & M_{12}^2(N)(\gamma_0\varepsilon)_i & D^2(N)(\langle\delta^2\rangle)_i\end{pmatrix} * \begin{pmatrix}\beta_0\varepsilon/(\beta_0\varepsilon)_i\\ \alpha_0\varepsilon/(\alpha_0\varepsilon)_i\\ \gamma_0\varepsilon/(\gamma_0\varepsilon)_i\\ \langle\delta^2\rangle/(\langle\delta^2\rangle)_i\end{pmatrix} \quad (3)$$

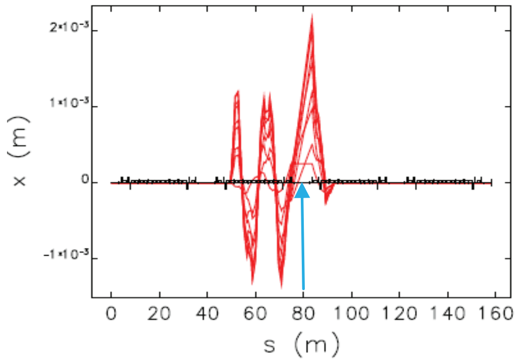

Figure2 Close orbit bump with four correctors in booster (the arrow indicates the extraction point)

LATTICE OPTIMIZATION

There are five quads used for changing the optics. The optimized optics are shown in Figure 3. The lattice optics change four times. The ratio of maximum to the minimum singular value of normalized matrix is 21.

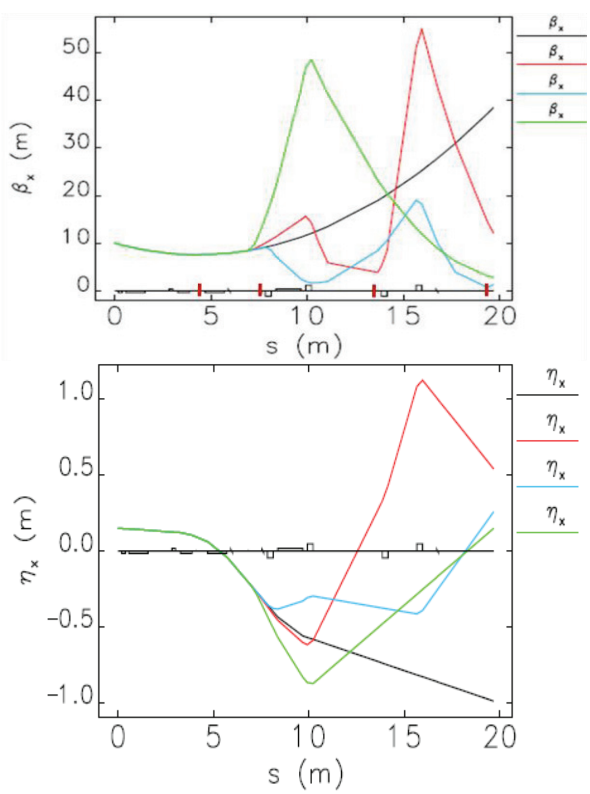

Figure 3 Optimized beam optics for measurement

The following error source effects are considered. The beam size measurement includes the flag resolution error and beam size increase due to the ripple error from the extraction kicker. The matrix measurement error includes the flag resolution, dispersion error, ripple error in the transport line and beam reproducibility from booster.

The code Elegant was used to simulate the measurement. [4] The fitted parameter values are listed in Table II, which includes results with three sets of optics and four sets of optics. To check whether it is possible to fit data with fewer optics changes, figure 4 shows the fitted beam emittance square with 2, 3 and 4 sets of optics. With 2 set of optics, the ratio of max. to min. singular value of $\hat{R}$ matrix is 38 and there are many chances to fit the unrealistic values, i.e. the emittance square is negative. With 3 sets of optics, the ratio of the maximum to the minimum singular value is 30. The fitted values have less chance to be negative and unphysical. Adding a four set of optics increases the measurement accuracy. The fitted emittance and the energy spread are very close to the simulation input values.

Table II: Fitted beam parameters with different optics set

Parameter	Input	3 set of optics	4 set of optics
ε (nm-rad)	50.0	43.1±14.8	49.4±11.7
δ (%)	0.1	0.126±0.027	0.112±0.032
β_x(m)	10.0	13.9±6.16	11.4±2.46
α_x	0.57	0.50±0.20	0.52±0.20

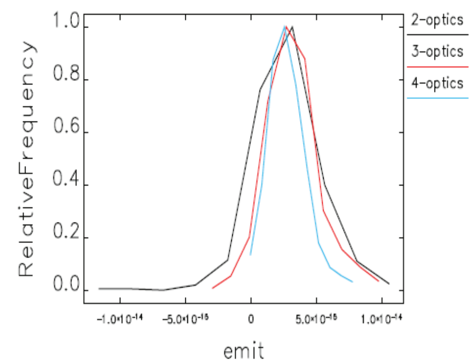

Figure 4 Fitted beam emittance with different number of optics

CONCLUSION

SVD was used to measure the beam emittance and energy spread when they cannot be decoupled. The singular values of normalized matrix qualitatively indicate the measured data accuracy and their error sensitivity. This is used in the lattice optimization with minimum number of optics change while keeping the measured parameters accuracy.

The beam based measurement is simulated to measure the transport line matrix. Four correctors in the booster are used to excite different beam trajectories into the transport line. The measured beam emittance and energy spread are very close to the simulation input values.

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