# EXPERIMENTAL CALIBRATION OF VUV RING OPTICS

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*Abstract*

The individual quadrupole gradients, undulator focusing, beam position monitor (BPM) gains, and orbit steering magnet calibrations in the NSLS VUV Ring were determined by analyzing the measured orbit response matrix with the computer code LOCO[1] (Linear Optics from Closed Orbits). The measured orbit response matrix is the change in orbit at the BPMs with changes in steering magnet excitation. The analysis showed beta function distortions of $\pm 35\%$ and $\pm 25\%$ horizontally and vertically. The design periodicity of the optics was restored by adjusting the quadrupole gradients to restore the periodicity of the response matrix. This lead to an increase of about 18 percent in the beam lifetime at 500 mA with a slight (3 and 7 percent) decrease in both the horizontal and vertical electron emittances as determined from the beam sizes measured using a synchrotron light monitor.

## 1 INTRODUCTION

The VUV Ring is an 800 MeV storage ring at Brookhaven National Laboratory that has been producing synchrotron radiation for experiments since 1983. The storage ring magnet lattice has the Chasman-Green lattice [2, 3], a design that has been subsequently adopted by many of the third generation light sources.

The lattice consists of four super periods, each with a dispersion-free straight section (for injection, RF cavities and two insertion devices) and a double-bend achromat having a quadrupole doublet that provides the achromatic focusing (QAs). The dispersion-free straight sections have a symmetric pair of horizontally focusing quadrupoles (QFs) and horizontally defocusing guadrupoles (QDs). The magnet layout is shown at the top of Figure 1. This design should produce linear optics with a four-fold periodicity, if within each of the three quadrupole types, the individual magnets have the same gradients. This periodicity is broken primarily by the focusing effects of the two insertion devices, but also by field gradient errors from quadrupole magnet construction tolerances and orbit offsets in sextupoles, which contribute a linear focusing effect on the beam. To better control the periodicity breaking due to the insertion devices, the QFs and QDs in each of these straight section were seperately powered. The calibration of the gradients in these seperately powered quadrupoles provides another source of periodicity breaking, even with the undulators removed from the ring. The total number of independent focusing parameters is determined by the seven quadrupole powers supplies that control the gradients in the seven families of quadrupoles ( 3-QFs, 3-QDs and 1-QAs).

Despite the additional power supplies, optics measurements indicated that the $\beta$-functions varied significantly from the design 4-fold periodicity. This break in periodicity of the lattice functions degrades the performance of the ring from the design. The work described in this paper was undertaken to better understand the sources of the break in periodicity and derive the settings for the quadrupole power supplies that best restores the design optics.

## 2 OPTICS ANALYSIS

The VUV Ring optics were characterized by analyzing the measured orbit response matrix with the computer code LOCO [1]. The orbit response matrix, $M$, is defined as

$$\begin{pmatrix} \boldsymbol{x} \\ \boldsymbol{y} \end{pmatrix} = M \begin{pmatrix} \boldsymbol{\theta}_x \\ \boldsymbol{\theta}_y \end{pmatrix}, \tag{1}$$

where $\boldsymbol{x}$, $\boldsymbol{y}$ are the shift in closed orbit at the BPMs for a change in steering magnet excitation $\boldsymbol{\theta}_x$, $\boldsymbol{\theta}_y$. LOCO adjusts the parameters of a computer lattice model (in this work we used a MAD [4] model) in order to minimize the $\chi^2$ difference between the model, $M_{\text{mod}}$, and measured, $M_{\text{meas}}$, response matrices.

$$\chi^2 = \sum_{i,j} \frac{(M_{\text{mod,ij}} - M_{\text{meas,ij}})^2}{\sigma_i^2}, \tag{2}$$

where the $\sigma_i$ are the measured BPM rms noise levels. For the VUV Ring analysis, we used a model with no coupling between horizontal and vertical planes. We did not use the coupling terms in the response matrix (e.g. the shift in vertical orbit when changing horizontal steering magnets). Only the normal gradients in the quadrupoles were fit. The VUV Ring has 24 BPMs that read in both the horizontal and vertical planes. Sixteen horizontal and 16 vertical steering magnets were used to measure the response matrix, so a total of 768 data points were used in the statistical fit.

In order to minimize the number of parameters used in the fit and thus maximize the accuracy of the fitted magnetic gradients, the response matrix was first measured with all sextupoles turned off and all insertion devices open. The parameters varied to fit this response matrix included the individual gradients in the 24 quadrupoles, the dipole gradient, the horizontal and vertical gains of the 24 BPMs, and the calibrations of the 32 steering magnets. In addition, the energy shifts associated with changing the 16 horizontal

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steering magnets were varied in the fit. When a horizontal steering magnet is changed, there is a shift in the electron energy and an associated shift in the closed orbit proportional to the dispersion. This shift is not included in the model. To account for this, an orbit shift proportional to the measured dispersion was added to the model response. The proportionality constant for the dispersion was fit, and the fit result is the energy shift for each horizontal steerer. In all, 121 parameters were used to fit the 768 data points in the response matrix. After the fit, the measured orbit response matrix differed from the model by 2.2 $\mu$m rms compared to the measured BPM rms noise level of 1.6 $\mu$m.

Then the sextupoles were turned on and the response matrix was measured again. This second matrix was used to calibrate the gradients in the sextupoles. Response matrices were also measured after closing each of the insertion devices. These were used to calibrate the vertical focusing associated with each insertion device.

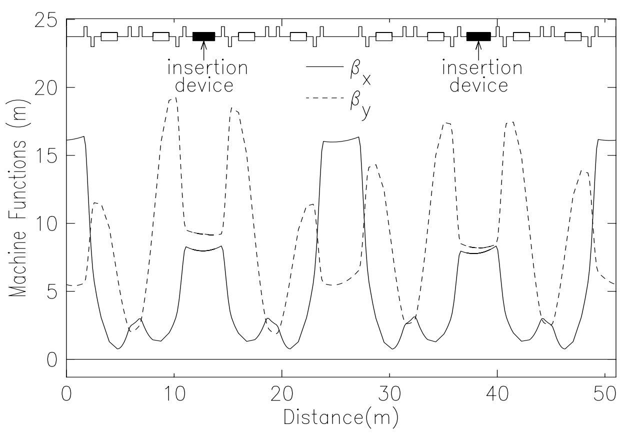


Figure 1: The $\beta$-functions in the NSLS VUV Ring calculated by LOCO as described in Section 2, before the periodicity restoration described in Section 3 was applied.

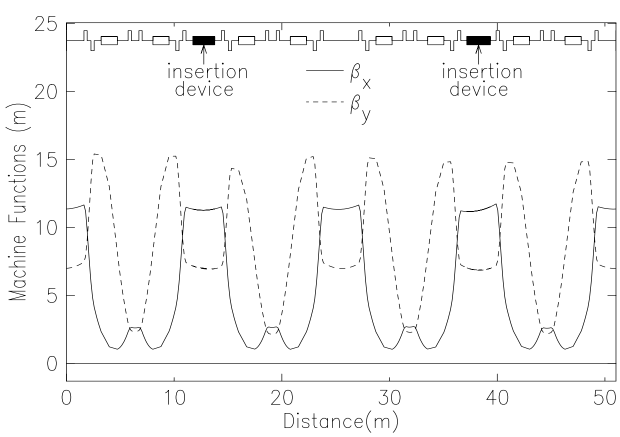


Figure 2: The $\beta$-functions in the NSLS VUV Ring calculated by LOCO as described in Section 2, after the periodicity restoration described in Section 3 was applied.

In this way we arrived at a complete model of the VUV Ring focusing optics. Figure 1 shows the $\beta$-functions for this model. This model was measured with the maximum focusing effect ( smallest gap and maxiumum strength parameter, K= 7.6) for the second insertion device (at the right hand end) of the lattice. The effect of this insertion device on the vertical $\beta$-function is clearly seen when compared to the weaker insertion device (K$\approx$1) at the left hand end of the lattice. As had been expected, the distortions from the periodic design were large (up to $\pm 35\%$ horizontally and $\pm 25\%$ vertically). The injection straight section had been observed to have an increased radiation loss during injection with the insertion device gap closed, consistent with the larger $\beta_x$ predicted by LOCO in this region.

## 3 PERIODICITY RESTORATION

Section 2 described a method for determining a model of the individual gradient errors in each of the VUV magnets - the quadrupoles, sextupoles, and insertion devices. In this section we present a method for finding those quadrupole power supply settings that compensate for these errors and restore the design periodicity. The method has also been used successfully at the ALS [5]. The algorithm is similar to orbit correction, where one does not usually try to find the specific dipole errors that caused an orbit shift. Instead one trys to find the changes in orbit steering magnet excitation that would best reproduce the orbit shift, then applies just the opposite steering magnet changes to cancel the orbit shift.

In this case we model the break in four-fold periodicity by the gradient difference between the quadrupole families (one gradient for all quadrupoles with a common power supply) that best reproduces the measured response matrix. We look at the variation in the gradients between the three different QF families and between the three different QD families. Then we adjust the power supplies in the ring so that the fit gradients for the three QF families are the same and the three QD families are the same. In this way, the quadrupole power supplies are adjusted to maximize the periodicity of the measured response matrix.

The response matrix was measured with insertion devices closed and sextupoles on, the normal operating condition for the ring. Then we first performed the analysis described in Section 2 on this matrix, in order to fix the calibrations of the BPMs, the steering magnets and the energy shifts of the horizontal steering magnets. Then we took as a ”model” of the storage ring a lattice with zero gradient errors in the sextupoles and insertion devices and with no individual quadrupole gradient errors (i.e. all quadrupoles in each family have the same gradient). The $\chi^2$ difference between the model and measured response matrix was minimized by varying only the 7 quadrupole family gradients. If the fitted values for the gradients in the 3-QF and 3-QD families differ, this means they could be changed to improve the periodicity of the response matrix. Then the power supply current, $I_i$, for each of the three QF and QD families was changed as follows:

$$(I_i)_{new} = (I_i)_{old} \frac{< K >_{QF}}{K_i}, \quad (3)$$

where $K_i$ is the fitted gradient for the i-th QF family and $< K >_{QF}$ is the average of the $K_i$ over the individual quadrupoles in all the QF families. The power supply currents were similarly corrected in the 3-QD families. The current in the one QA family power supply was not changed, since it already had the required periodicity in the ”model”.

The changes predicted by Equation (3) were applied to the 3-QF and 3-QD power supplies in the VUV ring and the linearity of the change in the quadrupole field gradients (assumed in Eq. (3)) were verified using the available high precision Hall probe installed in one magnet of each quadrupole family. The resulting lattice had its response matrix measured and analyzed using the non-periodic model of the ring as described in Section 2. The calculated $\beta$-functions resulting from this new lattice of VUV ring are plotted in Figure 2. The resulting distortions from the four-fold design periodicity are greatly reduced: $\pm 3\%$ horizontally and $\pm 4\%$ vertically. The larger vertical periodicity breaking resulting from the large periodicity breaking of the vertical focusing effects of the two very different insertion devices.

## 4 IMPROVEMENT IN THE VUV RING PERFORMANCE

Several properties of the VUV Ring operation were improved with the increased four-fold periodicity obtained from the changes in Section 3. Measurement of the transverse profile of the beam with a focused synchrotron light monitor, showed a 3$\%$ and 7$\%$ reduction in the horizontal and vertical emittances, respectively. This resulted from the reduction in the larger variations of the $\beta_x$ in the dipole magnets and the skew quadrupoles in the original lattice compared to the restored periodicity lattice. Despite this decrease in transverse emittance, the lifetime of the beam increased at all currents, as shown in Figure 3. This increase was about 15$\%$ at 850 mA and increased to about 18$\%$ at 550 mA. Calculations of the Touschek scattering lifetime with the program ZAP[6], using the calculated $\beta$-functions and the measured emittance showed an increase of 50 to 65$\%$ in the lifetime coming mostly from the reduction in the $\beta_x$ in the long straight sections without insertion devices. This prediction was observed by comparing the radiation loss rate in detectors installed in these straight sections, which measured a 62 to 68$\%$ reduction in loss rate depending on current after the periodicity restored lattice was implemented. The difference of the total lifetime improvement from this loss rate could be due to changes in gas scattering partial lifetime due the increase in the $\beta_y$ in parts on the ring.

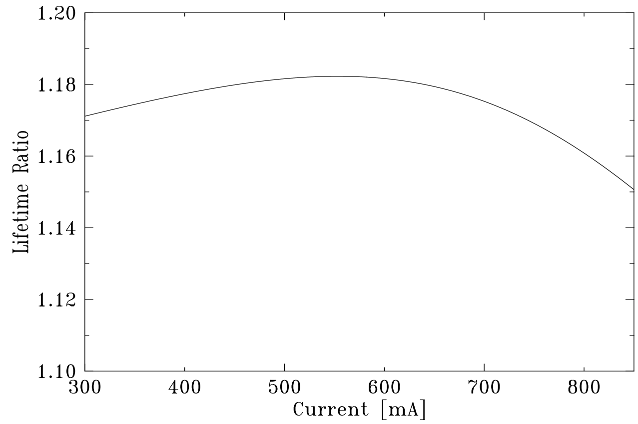


Figure 3: The measured increase in beam lifetime versus current after the periodicity restoration relative to before restoration.

## 5 CONCLUSION

Measurement of the the actual lattice properties of the the VUV Ring at NSLS yielded a model of the periodicity breaking of the focusing optics in the Ring. This model made it possible to predict a method of restoring the four-fold periodicity of the lattice functions. Changing the focusing optics as predicted by this model yielded significant improvement in beam lifetime while at the same time making slight reductions of the measured beam emittance. This improvement was attributable to the reduction of the peak to peak variations of the ring $\beta$-functions.

## 6 REFERENCES

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