VERTICAL EMITTANCE AT THE QUANTUM LIMIT

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Abstract

Further reduction of betatron coupling and vertical dispersion in the storage ring of the Australian Synchrotron Light Source has resulted in the achievement of a beam vertical emittance that is now dominated by the intrinsic quantum effects. This paper will detail the key elements in achieving a vertical emittance at the quantum limit and results achieved.

INTRODUCTION

Previous work in vertical emittance minimization at the Australian Synchrotron Light Source has resulted in achievement of vertical emittance of the order of 1 pm rad [1]. Since then, a systematic survey of magnet misalignments using beam based methods has been conducted [2] which yielded very promising results for minimized vertical emittance after both sextupole offsets and quadrupole rolls had been corrected. This paper will give a brief overview of the correction methods used and show the results of a detailed study of the beam lifetime at minimized emittance, which indicated that we have achieved a vertical emittance that is comparable to the quantum limit.

MAGNET ALIGNMENT

A summary of the study in [2] will be presented here for clarity. The measurements of magnet misalignments were obtained by analysis of the orbit response matrix through LOCO [3] to extract the skew quadrupole field component in each magnet. Sextupole induced skew components (from vertical effects) were isolated by shunting the strength of the sextupole magnets individually. Quadrupole induced skew components (from a rolled girder) were isolated by turning all the sextupoles off. Vertical misalignments of sextupole magnets were corrected from a mean offset of 70 μm to less than 10 μm and quadrupole roll errors, which where measured as high as 0.6 mrad in some girders, were all corrected to below 0.2 mrad.

VERTICAL EMITTANCE MINIMIZATION

While some refinements in data collection and consistency have been made, the vertical emittance minimization technique used at the Australian Synchrotron Light Source (ASLS) is largely consistent with that previously used in Ref. [1]. An orbit response matrix is taken to measure the uncorrected coupling and dispersion of the storage ring. This is analyzed using LOCO and a model of the ring with skew quadrupole components fitted to every multipole magnet is produced. This model is then run through a iterative minimization algorithm to find the arrangement of available skew quadrupole settings that will simultaneously minimize both betatron coupling and vertical dispersion. The minimization algorithm can also be set to arbitrary emittance goals, allowing a variety of vertical emittances to be set.

After the multipole magnets were all realigned, simulations and preliminary measurements showed that a vertical emittance of 0.8 pm could be achieved, a 50% improvement on previous efforts. It was also noted that an anomalously high skew correction had to be applied in one sector of the storage ring to achieve this correction. This correction had been present in previous emittance minimization but it had been hoped that the magnet re-alignments would largely eliminate it. While the emittance minimization algorithm is normally programmed to only use the existing 28 skew quadrupoles in the ASLS storage ring as actuators for coupling correction, there are an additional 28 un-powered skew quadrupole windings (secondary windings on sextupole magnets) in the storage ring. The minimization was run with both 28 and 56 skew quadrupoles in the model to determine if there would be significant benefit from having more skew quadrupole power supplies installed. It was found that another factor of 2 in emittance correction could be achieved, primarily by moving the anomalously high correction from the current skew quadrupole to the next un-powered skew quadrupole winding on the magnet 2 m downstream. This indicates that there was a strong source of local coupling in or near that magnet (Fig. 1), although we have not been able to determine the exact cause.

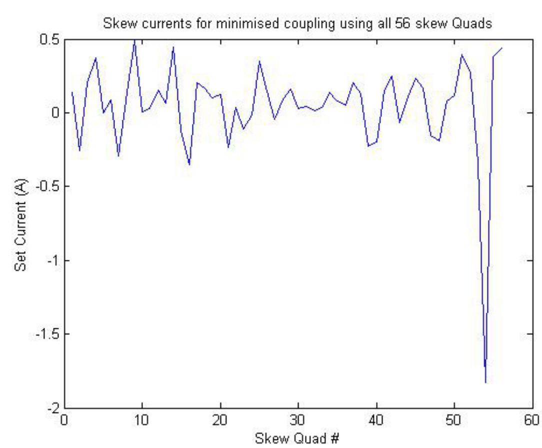

Figure 1: Skew quadrupole current settings determined by the emittance minimization algorithm applied to all 56 possible locations, showing the anomalous correction required.

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In response to this analysis, power supplies for 4 additional skew quadrupoles were installed around this section of the storage ring and incorporated into the emittance minimization.

VERTICAL EMITTANCE MEASUREMENTS

The present work employs the method of Ref. [1] for indirect measurement of vertical emittance using the Touschek lifetime. Complementary work continues towards direct measurement of vertical emittance using the vertical undulator method [4]. Measurement of vertical emittance below $\varepsilon_y = 1$ pm rad requires magnetic measurement of the installed insertion device, which has not yet been realized.

Touschek Lifetime Measurements

Touschek scattering is the process in which electrons in the bunch scatter off each other with large momentum transfer such that they escape the momentum acceptance of the RF bucket [5]. The Touschek lifetime is given by equation 2,

$$\begin{aligned} \frac{1}{\tau} &= \frac{N r_e^2 c}{8\pi\sigma_z\gamma^2}\left\langle\frac{D(\epsilon)}{\delta_{max}^3\sigma_x\sigma_y}\right\rangle \qquad (1)\\ \epsilon &= \left(\frac{\delta_{max}\beta_x}{\gamma\sigma_x}\right)^2\\ D(\epsilon) &= \sqrt{\epsilon}\Bigg(-\frac{3}{2}e^{-\epsilon}+\frac{\epsilon}{2}\int_\epsilon^\infty\frac{e^{-u}\ln u}{u}du\\ &\quad+\frac{1}{2}(3\epsilon-\epsilon\ln\epsilon+2)\int_\epsilon^\infty\frac{e^{-u}}{u}du\Bigg) \end{aligned}$$

where N is the number of electrons in the single bunch, r_e is the classical electron radius, $\sigma_{x,y,z}$ are the rms bunch sizes, δ_{max} is the energy acceptance of the ring as determined by RF acceptance and dynamic aperture.

The scattering rate is sensitive to the RF momentum acceptance (and hence RF voltage) and density of the electron bunch (beam volume). As the emittance of the beam will determine the beam volume (for a constant beta functions), it is possible to infer the beam emittance in one dimension from the Touschek scattering lifetime, if all other parameters are known well.

The Touschek lifetime analysis was carried out as detailed in [1], a brief summary will be given here for clarity. A single bunch was filled to 8 mA current such that the lifetime becomes heavily dominated by Touschek scattering processes. The stored beam current decay was observed for 10 minutes. The Touschek lifetime parameter is extracted from this decay curve by fitting for the current dependent component via

$$\frac{di}{dt} = -\frac{i}{\tau} - \frac{i^2}{T} \qquad (2)$$

$$i(t) = \frac{i_0 T e^{-\frac{t}{\tau}}}{T + i_0\tau(1-e^{-\frac{t}{\tau}})} \qquad (3)$$

where T is the Touschek parameter (mA hrs) and τ is the normal gas scattering lifetime (hrs).

The RF voltage is then varied to lower the momentum acceptance, and the process is repeated. Measurements were conducted at 6 different RF voltages between 2 and 3 MV total voltage. A curve of the Touschek scattering parameter is then fit to these measured beam lifetimes by using the known horizontal and longitudinal beam sizes (including potential well distortion) and momentum acceptance as constants and varying the vertical emittance.

In a refinement of the technique, the potential well distortion effect on the longitudinal beam size is calculated using the impedance model obtained from previous single bunch measurements [6] and confirmed with recent measurements. It was previously based on the bunch lengthening factor observed for a 8 mA bunch at 3 MV RF potential, however it was realized that this lengthening factor would be less for lower voltages. The new model accounts for the increase in bunch length with decreasing RF voltage, and re-analysis of the old results shows a slight rise in the fitted emittance as a result.

Measurements were conducted largely under the same lattice conditions as earlier experiments to allow for a direct comparison of results. In figure 2 we can see the plots of the older 2010 measurements with the recent 2013 measurements under the same conditions. In figure 3 we show the more recent measurements in more detail. We also include new measurements conducted in 2014 with a low chromaticity lattice setting (normal operation is with quite high vertical chromaticity to passively control instabilities). The low chromaticity settings result in a lower achievable coupling as the sextupole fields, and hence the induced skew fields from misalignment, are significantly lower. The low chromaticity lattice also has a larger momentum acceptance than the RF, so we do not see the ‘turnover’ in the Touschek lifetime at 2.9 MV anymore. The low chromaticity data was also taken after the effect of spin polarization was noticed (discussed below), as so extra care was taken during the measurements to minimize this effect.

Spin Polarization Effect

It was observed for some data sets that some data points would be inconsistent with the fitted curve. This was particularly apparent for the extremely low emittance results and where there had been a delay in data taking after injection of current. It was hypothesized that the beam spin polarization may be having an effect. The spin polarization time for the ASLS storage ring is 14 minutes [7], which is comparable to the measurement time. To investigate this, the vertical emittance was minimized to 0.4 pm and the single bunch lifetime measurements were taken. One set of measurements were done with ‘fresh’ beam - ie. the beam was dumped after each measurement and a fresh bunch injected. The other set of measurement were done with ‘old’ beam, where the measurement was conducted 15 minutes after injection. The results in Fig. 4 show a clear effect of approximately a 10% increase in fitted vertical emittance

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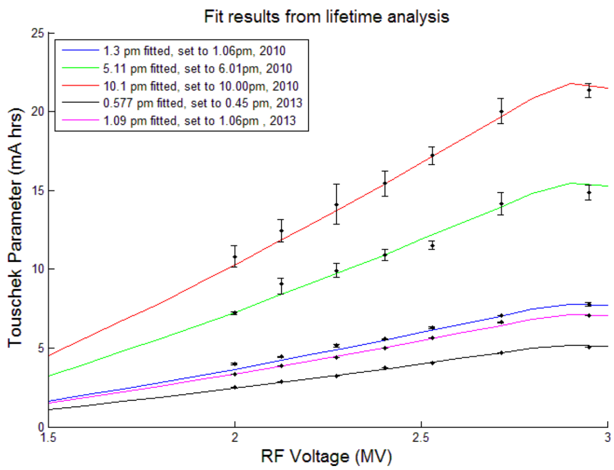

Figure 2: The data points show the extracted Touschek parameter from the measured current vs. time measurements. The fit lines are the results of eq. 1 evaluated with the beam parameters set to measured values except for the vertical emittance, which is allowed to float. The result is then the ‘fitted’ value for the emittance, as opposed to the ‘set’ values, which was obtained from ORM analysis. Shown here are the older results from 2010, combined with more recent measurement taken in late 2013 after magnet realignments were completed.

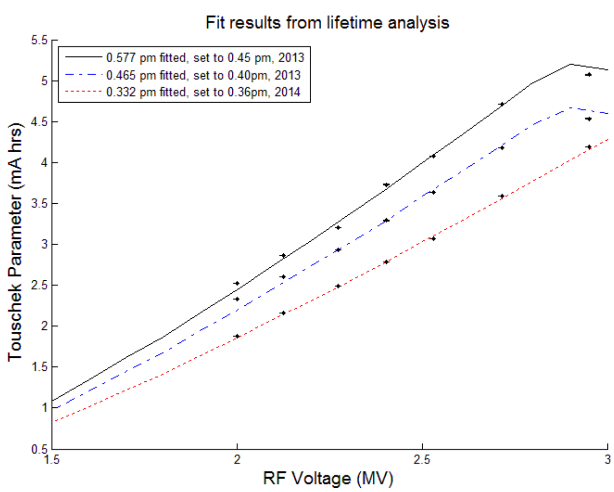

Figure 3: The most recent results from 2013 at high chromaticity are shown, along with the latest minimization result conducted at chromaticity of 1 in both planes, taken in early 2014. The ‘set’ emittance shown in the legend is the vertical emittance of the beam as calculated from the ORM measurement and then added in quadrature with the quantum limit of 0.35 pm.

due to the increased lifetime from a polarized beam. Future in-depth analysis of the data will take this into account by making sure the beam has been freshly injected and by investigating the effects of shortening the collection period from 10 to 5 (or less) minutes.

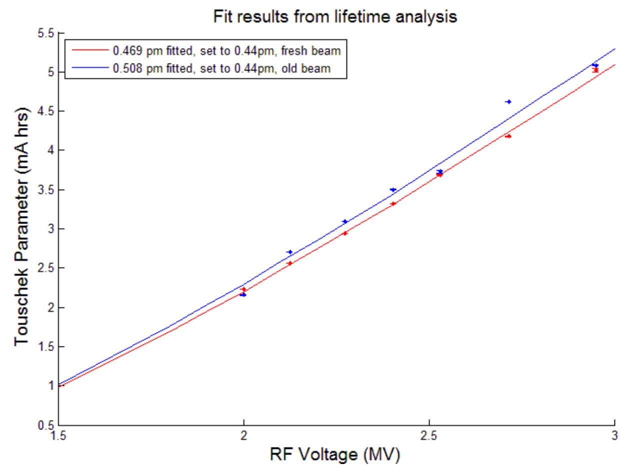

Figure 4: Lifetime analysis showing the effect of beam polarization. The blue data points were obtained using the exact same conditions as the red, except for waiting at least 15 minutes after injection. They show a longer lifetime, as expected and more noise in their distribution compared to the red data points of largely unpolarized beam.

CONCLUSIONS

The fit results from the low chromaticity condition indicate a vertical emittance of 0.33 pm (with error margins to be determined) and the quantum limit for the ASLS storage ring is about 0.35 pm. There is some work to be done in regards to isolating spin polarization effects and determining error contributions, however these recent results suggest we have entered the regime where the quantum limit of vertical emittance is now the limiting factor in what we can achieve. The result also indicated we have been able to achieve an emittance ratio of 3×10^{-5} through careful attention to multipole alignment and positioning of skew correctors. A more detailed exploration of the Touschek lifetime analysis, including error analysis is currently being conducted.

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