Achieving and Measuring Sub-Micrometer Beam Stability at 3rd Generation Light Sources

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Abstract. Electron beam stability at the source points of synchrotron radiation is an accepted requirement for the preservation of the low emittance provided in 3rd generation light sources. With emittances approaching 1nm rad this typically requires sub micrometer positional stability at the source point over time scales from milliseconds to at least hours and ideally much longer. These challenges are routinely met by the use of fast orbit feedback systems. This contribution sets out to first establish a relevant representation of stability over many orders of magnitude in time and looks at available stable references. To complement this, data on the electron and X-ray beam stability achieved at various operational light sources is compared.

1. Introduction
The topic of positional and angular stability of the electron beam at the source point of synchrotron light sources has been shown to be paramount to the preservation of the low emittance generally found in 3rd generation light sources [1, 2]. These authors have identified the different impact of 'fast' or 'slow' positional instabilities: While 'fast' motion or vibration (within the integration period of an experiment) will be integrated over and thus only add in quadrature to the beam size or divergence, any 'slow' motion will be resolved and might thus become observable directly as a variation of beam position or intensity (if slits define the position) in the experiment at a beamline.

Electron beam size $\sigma_e$ and divergence $\sigma'_e$ at the source point depend on beta function $\beta$, emittance $\epsilon$, energy spread $\sigma_E$ and dispersion $\eta$. For simplicity it is assumed that $\beta' = \eta' = 0$ which is typically valid at an ID source point in the centre of a straight.

$$\sigma_e = \sqrt{\beta \epsilon + \sigma_E^2 \eta^2} \quad \sigma'_e = \sqrt{\frac{\epsilon}{\beta}}$$  (1)

The relevant electron beam parameters at the source point of current light sources provide vertical beam sizes which are now typically in the order of around 5 μm [3]. This is mainly the result of a general trend to lower the horizontal emittance, with the most recently built light sources now operating at around 1nm rad. But also in existing light sources improved methods of reducing the emittance coupling ratio and thus the vertical emittance to values as low as 1-2 pm rad can lead to vertical beam sizes of just a few μm [4, 5]. On the other hand, horizontal beam sizes will remain one or two orders of magnitude larger than vertical beam sizes until the first of a new class of 'ultimate storage rings' will be realised [6].
As a result, even with the generally accepted target of keeping the RMS variation of electron beam position (and pointing angle) to 10% of RMS beam size (and divergence), this now requires sub-µm stabilisation in the vertical plane, while the requirements for the horizontal plane are typically relaxed and are thus easily met as a consequence of the efforts going into stabilisation of the vertical beam position and pointing angle.

This contribution intends to document how well a sample of operating light sources meets the requirements of electron beam stability by employing good engineering practice (solid foundations, quiet accelerator vaults), widespread use of global fast orbit feedback systems, and additional stabilisation using X-ray beam position monitors (XBPMs). It also proposes the use of the Allan deviation [7] as a measure of stability that is able to quantify the achieved stability over a large variety of time durations from ms to weeks. Within the frame of this paper, only source points in the centre of insertion device (ID) straights will be looked at, as these are generally more demanding than bending magnet source points.

2. Source point movements and their impact on beamlines

Most beamlines can be assigned to one of a few basic optics, neglecting any monochromator:

- The ID light illuminates a set of primary slits (secondary source), which is then focussed onto the sample. In this case, neither changes of electron beam position nor pointing angle will lead to any change of position at the focus, only the intensity will vary as a result of how the slits are illuminated.
- The ID light is left to expand without any focussing to illuminate a large sample, possibly collimated by slits to shape the illumination.
- The source point in the ID is directly focussed onto the sample. In this case any electron beam position changes will be directly visible as the same relative (to beam size) motion, while pointing angle changes will cause a change in the illumination of the focussing elements.

In all three cases the photon beam position offset $\Delta y_{ph}(L)$ at a distance $L$ from the source point in relation to the photon beam size $\sigma_{ph}(L)$ can be shown to be directly related to the pointing angle error $\Delta y'_e$ relative to the photon beam divergence $\sigma'_{ph}$, since the contributions from the electron beam size $\sigma_e$, the radiation beam size $\sigma_r$ and in fact the beam position offset $\Delta y_e$ are not significant in this case due to the large $L$:

$$\sigma_{ph}(L) = \sqrt{\sigma_e^2 + \sigma_r^2 + L^2 \sigma_{ph}^2} \approx L \sigma'_{ph}$$

(2)

$$\Delta y_{ph}(L) = \Delta y_e + L \Delta y'_e \approx L \Delta y'_e$$

(3)

$$\frac{\Delta y_{ph}(L)}{\sigma_{ph}(L)} \approx \frac{\Delta y'_e}{\sigma'_{ph}}$$

(4)

Assuming a Gaussian intensity profile, the amount of light passing through a pair of slits of given width is the integral over the distribution within the extents of the slits. Any variation of the beam position will then be converted into a variation of intensity [2]. This can be extended to a random beam motion characterised by its RMS, which then results in an RMS intensity variation. It should also not be neglected that the intensity variation will be higher if the beam is not centered on the slits, as might happen as a result of a slow drift. For example, for a Gaussian shaped beam of $\sigma$ RMS width instead of a 0.5% RMS intensity variation resulting from a typical 10% RMS beam centroid motion on centered ±1σ slits, with a 1σ offset the intensity variation will become 7%.
Table 1. Electron beam parameters at the centre of a (low beta) straight as used for comparison with beam motion. The use of a fast orbit feedback (FOFB) system is also shown.

| Ring/Plane | FOFB | $\epsilon$ [nm rad] | $\beta$ [m] | $\eta$ [mm] | $\sigma_E$ [%] | $\sigma_e$ [\mu m] | $\sigma'_{e}$ [\mu rad] |
|-----------|------|---------------------|------------|-------------|--------------|-----------------|------------------|
| ALBA/H    | No   | 4.5                 | 2.06       | 82.6        | 0.11         | 132             | 47.4             |
| ASLS/H    | No   | 10.3                | 9.05       | 100         | 0.1          | 321             | 33.7             |
| ESRF/H    | Yes  | 4                   | 0.35       | 31          | 0.11         | 72              | 100              |
| DLS/H     | Yes  | 2.7                 | 4.65       | 52          | 0.096        | 123             | 24.1             |
| Soleil/H  | Yes  | 4.4                 | 4.6        | 165         | 0.1          | 221             | 30.5             |
| ALBA/V    | No   | 0.023               | 1.22       | 0           | 0.11         | 5.2             | 4.3              |
| ASLS/V    | No   | 0.12                | 2.42       | 0.7         | 0.11         | 17              | 7.06             |
| ESRF/V    | Yes  | 0.007               | 2.96       | 0           | 0.11         | 4.6             | 1.53             |
| DLS/V     | Yes  | 0.027               | 1.53       | 0           | 0.096        | 6.4             | 4.2              |
| Soleil/V  | Yes  | 0.033               | 2.36       | 0           | 0.1          | 8.7             | 4.6              |

Figure 1. Integrated motion (left) and angular motion (right) relative to the respective vertical (solid) and horizontal (dashed) beam sizes: ALBA (green), Australian Synchrotron (ASLS) (red), ESRF (purple), Diamond Light Source (DLS) (yellow), Soleil (blue)

3. Short term stability of a sample of light sources

The short term stability of the electron beam at the centre of a straight and of the ID photon beam can be assessed directly from synchronous readings of upstream and downstream electron beam position monitor (EBPM) data. It has been shown that modern EBPMs provide enough resolution to reliably predict the short term (up to a few seconds) photon beam motion [8], as long as ID movements are excluded (as integral field errors could lead to changes of the trajectory through the straight while not impacting on the EBPM readings). Electron beam position at the centre of the straight is computed as the average of upstream and downstream EBPM readings, while the pointing angle is the difference of the two readings divided by the physical distance of the two EBPMs.

A snapshot of the typical positional and angular stability achieved in operation of a few light sources has been generated from 10 s of EBPM data (figure 1). For this comparison, all motion has been normalised to the respective beam sizes as summarised in table 1. The graphs of integrated motion display the RMS displacement within a frequency band from 0.1 Hz up to the
indicated frequencies. In contrast to power spectral density (PSD) graphs, integrated motion graphs provide a direct comparability between the contributions from noise and individual sharp spectral lines (whose intensity cannot be correctly reflected on PSDs). However, due to the integral starting at the lowest frequency, integrated motion graphs are limited to relative short (a few seconds) observations, as otherwise the integral will be dominated by the first few frequency points.

It can be seen that for frequencies up to a few 10 Hz, all of these light sources are very stable with motion of no more than 2% of beam size or divergence, and are some considerably better, even though not all are operating with a fast orbit feedback (FOFB) system. At higher frequencies of a few 100 Hz, most are approaching the 10% mark, often there is a considerable contribution at the 50 Hz mains frequency, which is evidently true orbit motion (not contamination in the EBPM electronics, as it is absent on some light sources and absent in lab tests, and all these establishments use the same type of instrumentation). The mechanisms of coupling mains to orbit motion can be manifold (e.g. power supply ripple, mains cables too close to beam, fans or other rotating machinery close to beam) and it is beyond the scope of this paper to investigate to what degree various light sources have attempted to reduce these. It should be noted that the chosen way of displaying motion normalised to beam size reveals there are various ways to perform well: where a small vertical coupling and beam size is chosen (as for instance at ESRF), a reasonable performance FOFB will ultimately only provide the same level of short term stability as does the choice of a larger beam size and no FOFB like currently at ASLS. It should also be kept in mind that all feedback systems will enhance the noise at higher frequencies (above about 100-200 Hz), and that if beam motion is present in this range (as could be caused by noisy water cooling) it will lead to a steep increase of integrated motion as seen in the data for DLS.

In summary, this performance will be more than adequate for as long as exposure times or sample periods at beamlines remain slower than 20 ms. At higher acquisition speeds, certain features of the source point movements could be revealed in particular if narrow slits (or poor alignment) are used and experiments are very sensitive to small intensity variations.

4. Long term stability and XBPM feedback

While short term stability can be adequately quantified by means of integrated motion, long term stability is better assessed using a different kind of mathematical analysis, in particular due to the general presence of a low frequency ‘random walk’. In the domain of frequency stability, the measure of ‘Allan Variance’ has been established within the long tradition of investigating and improving stability. This statistical measure has more recently also been applied in other fields [9], and is also known as a two sample variance:

\[
\sigma_y^2(\tau) = \frac{1}{2} \left\langle (\bar{y}_{i+1} - \bar{y}_i)^2 \right\rangle \quad \text{with} \quad \bar{y}_i = \frac{1}{\tau} \int_0^\tau y(i\tau + t) \, dt
\]  

The square root of this variance can be understood as the standard deviation of the differences between averages over a period \(\tau\), and as such gives a good indication of how much variation can be expected between successive observations (exposures, measurements) each integrating over a period \(\tau\). Allan Variance offers some merits in comparison to PSD graphs which have been used to display long term stability of the electron beam [10] like direct display of expected displacements (not displacement squared per unit frequency) and direct comparability of magnitudes in frequency ranges (no need to integrate over the range, which can be misleading to the naked eye when logarithmic frequency scales on PSD are used).

This method has been applied to study the long term stability of the photon beam as measured in the frontend of the I19 beamline at DLS using EBPMs and XBPMs. These XBPMs are of the tungsten vane type and measure DC current caused by photo emission and have been installed at
Figure 2. Allan deviation of angular motion relative to photon beam size on I19 at DLS calculated from various sources: by projection of upstream/downstream EBPMs (blue), from position at XBPM1 (green), from position at XBPM2 (red). For comparison, the respective Allan deviation from XBPM1 of another beamline without XBPM feedback is shown (purple).

Various facilities to complement the measurements of the EBPMs [11, 12, 13]. In this particular straight a slow feedback (1 s update rate) on the position reading from the second XBPM corrects for any angular drifts by putting offsets on the upstream and downstream EBPM demand values, which effectively steers the beam always to a fixed position in this XBPM by the corrections of the FOFB [14].

Figure 2 shows that for short averaging periods up to 1 s there is almost perfect agreement between the measurements from EBPMs and both XBPMs. The XBPM position readings have been converted to angular offsets using (3) thus assuming that actual source point movements are small enough to have no significant effect on XBPM position readings. At longer averaging periods, the EBPM calculated angular motion reduces further, however this is just a result of the continuous effort of the FOFB to suppress any offsets at the EBPMs, and the increasing effectiveness of the FOFB (suppression) at lowest frequencies. It does not reflect the true stability of the EBPMs, as any errors originating in the EBPMs will be misinterpreted by the FOFB as real beam movements and ‘removed’ by corresponding changes to the beam position.

The angular stability readings from the two XBPMs provide an independent, if by no means perfect, measure of stability. Again, they agree closely for averaging periods up to 300 s. Above that, XBPM2 continues to decrease as a result of the correction applied by the slow XBPM2 feedback. On the other hand, the Allan deviation for XBPM1, which only observes the position without any input to the feedback, starts to slowly rise again until it reaches 0.3% of photon beam size for an averaging period of 1 day. The value of the observing XBPM1 can be regarded as an upper bound of the achieved stability, since it will include both actual beam movements (mainly due to mechanical or electrical drifts of XBPM2) and uncorrelated errors due to XBPM1 drifts. For comparison, a similar measurement of the stability as observed on an identical XBPM1 in another frontend without XBPM feedback shows about one order of magnitude larger motion at the long averaging periods.

These results need to be qualified in various ways: Firstly, the XBPM feedback is currently only active during fixed gap operation of the ID. Secondly, for the actual calculation of the Allan deviations 3 subsets of data (only 1 minute of data at 10,072 S/s, only 1 hour of data
at 157 S/s, and the full 6 days of data at 0.61 S/s) were used. The lower sample rates were produced by averaging over 64 and 16,384 samples of the full speed data and have enabled the production of an analysis spanning 8 orders in averaging duration without the need to handle more than $10^9$ samples directly in the calculation. As a result, there are some places where the lines from the various subsets of data do not overlap, which means the particular hour (minute) was not representative of the average of all hours (minutes). Finally, this graph captures only the performance in one particular week and can thus not be entirely representative of the general performance, in particular for the longer averaging periods.

5. Conclusions
Short term stability has been analyzed by calculating integrated motion at the source point over frequency in the range of 0.1 Hz to 1 kHz. The assessed sample of 3rd generation light sources are shown to provide short term stability at the source point of only a few per cent compared to the electron beam size and divergence up to frequencies of several ten Hertz. Beyond that, disturbances at mains frequency and the tailing off of the suppression of the fast orbit feedback systems introduce more motion, which needs to be assessed on a case by case basis if beamlines start to use exposure times shorter than 20 ms.

For long term stability, the statistical measure of Allan deviation has been introduced as a useful tool to quantify the stability over many different averaging periods. Using this kind of analysis, it could be shown that the inclusion of a frontend X-ray beam position monitor in a feedback can further improve the long term stability by one order of magnitude under certain conditions. The achieved stability in this configuration is ultimately limited by the stability of the floor which acts as the common reference between electron and X-ray beam position monitors and beamline equipment.

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